ELECTRICAL
ENGINEERING
PAPERS

B. G. LAMME

Electrical Engineering Papers

Electrical
Engineering
Papers

By B. G. Lamme

This volume contains a collection of the most
important engineering papers presented
by Mr. Lamme before various technical societies, and published in
engineering journals and
elsewhere from time
to time

1919

Westinghouse Electric & Mfg. Co.
East Pittsburgh, Pa.

PREFACE

The papers of Benjamin G. Lamme have always interested American engineers. Distributed in many publications, some quite inaccessible to readers, it is indeed a fortunate circumstance which now makes available a collection of these papers for engineers, professors, instructors, and students, and all those interested in, and able to understand, the progress of electrical engineering.

Besides his achievements in the art of engineering, Mr. Lamme has been gifted with the faculty for clear expression and explanation, which is one of the rarest to be found in the engineering profession. The collection begins with his early paper on the Polyphase Induction Motor, which, in its time, was a primer of the characteristics and operation of such motors in the hands of the numerous users of these machines. Then follows a period in which he prepared few papers, but which was one of great personal activity. Then comes his epoch-making paper, in 1902, before the American Institute of Electrical Engineers in New York on the Single-Phase System of the Washington Baltimore and Annapolis Railway. Up to this time, the development of the electric railway systems, as a whole, was at a point of complete stagnation, in the utilization of 600 volts direct current, and this paper represented the first great and successful attempt to break away from established practice toward materially higher trolley voltages. Its advent gave an impulse to the entire subject of the electrification of railroads greater than any other it had ever received, leading to the complete abandonment of old and apparently well established standards, as well as to later attempts to meet the new conditions with higher direct-current voltages.

In 1904, there are two papers, one on a 10,000 Cycle Alternator, and another on the Synchronous Motor for Regulation of Power Factor. In the same year, he contributed a discussion to the subject of Single-Phase Motors which ranks as one of the clearest and most suggestive descriptions of this type of motor, which owes to him its development and use.

Recognizing the importance of closer relations with the American Institute of Electrical Engineers, we find him contributing, from time to time, papers on Commutation, on the Homopolar Dynamo, on Rotary Converters, on Turbo Generators, on Losses in Electrical Machinery, and on Engineering Education, etc. It is safe to say that these papers will be read in their present form by many who enjoyed them when they came out originally, and their contents will perhaps be more appreciated today than at the time when they were written.

To all those who have followed the development of electrical engineering in America during the past thirty years, and to all those who would like to know the historical development of electrical apparatus, the series of papers which appeared in the Electric Journal, on the History of the Railway Motor, of the Direct-Current Generator and of the Alternating-Current Generator and the History of the Frequencies, now collected for the first time, will form most interesting reading. Here Mr. Lamme had an opportunity to recount the work of himself and of his associates, adding to it the clarity and lucidity which have always marked his style.

I think those who have known Mr. Lamme's interest in education and in his instruction of young engineers will be glad to find reprinted in this volume two of his contributions on the subject of engineering education. The wholesome, sound sense which permeates these papers cannot fail to appeal to all, and to impress the reader with the sound judgment of their author.

Although these papers represent a work of thirty years, during which time Mr. Lamme has been continuously associated with the great company which bears the name of Mr. Westinghouse, yet I believe they do not complete his whole life work. Those of us who have had the good fortune to have known him for a score of years, or more, well know that many contributions will yet be made by him to the art and science of electrical engineering. The publication by the Westinghouse Company of this collection of Mr. Lamme's engineering papers on the anniversary of his first connection with this company, thirty years ago, represents a most dignified appreciation of his services to the entire engineering profession.

B. A. Behrend

April 2d, 1919.

Permission to reprint these papers has been granted by the owners of the copyrights and individual credit is given in the foreword of each paper.

CONTENTS

The Polyphase Motor.......5
Washington, Baltimore & Annapolis Single-Phase Railway.......40
Synchronous Motors for Regulation of Power Factor and Line Pressure.......56
Data and Tests on 10,000 Cycle Per Second Alternator.......68
The Single-Phase Commutator Type Railway Motor.......80
Comparison of Series and Repulsion Type A.C. Commutator Motors.......100
Comparative Capacities of Alternators for Single and Polyphase Currents.......114
Dampers on Large Single-Phase Generators.......142
Development of a Successful Direct-Current 2000 Kw Uni-Polar Generator.......148
Commutating Poles in Synchronous Converters.......173
Theory of Commutation and its Application to Commutating Pole Machines.......201
Physical Limitations in Direct-Current Commutating Machinery.......247
Regulation Characteristics of Commutating Pole Machines and Parallel Operation with Other Machines.......303
High Speed Turbo Alternators—Designs and Limitations.......312
Temperature and Electrical Insulation.......352
Temperature Distribution in Electrical Machinery.......363
Some Practical Considerations in Artificial Ventilation for Electrical Machinery.......385
Some Electrical Problems Practically Considered.......391
Some Controlling Conditions in the Design and Operation of Rotary Converters.......439
Sixty-Cycle Rotary Converter.......466
Iron Losses in Direct-Current Machines.......483
Iron Commutators.......509
Polyphase Induction Motor with Single-Phase Secondary.......515
A Physical Conception of the Operation of the Single-Phase Induction Motor.......521
Single-Phase Load from Polyphase Systems.......554
The Technical Story of the Frequencies.......564
The Development of the Alternating-Current Generator in America.......585
The Development of the Direct-Current Generator in America.......638
The Development of the Street Railway Motor in America.......713
Technical Training for Engineers.......746
Engineering by Analysis.......755

THE POLYPHASE MOTOR

FOREWORD—This paper was prepared in the early part of 1897, or over twenty-two years ago. It was presented at the twentieth convention of the National Electric Light Association at Niagara Falls on June 10, 1897, and was prepared for the purpose of illustrating the characteristics and properties of the Westinghouse Type C motor which, at that time, was beginning to attract much attention. This motor was radically new in that it had a "cage" type secondary winding for large, as well as small, sizes, whereas, it was generally believed that the cage type was only suitable for small power machines, due to lack of starting torque. In this paper, the author showed how the required higher torque was obtained in the new type of motor.

On account of its simplicity and absence of mathematical formulae, this paper has been used quite extensively for educational purposes and many thousands of copies have been issued in pamphlet form.—(Ed.)

INTRODUCTION

THE polyphase motor is usually treated from the theoretical standpoint, and the results obtained are of interest mainly to designers and investigators. Such treatment has been principally of a mathematical nature, the object being to show how the various characteristics of the motor may be predetermined. This is what the designer requires, but it gives very little information to the practical man, who uses the motor. In the following treatment of the subject, the general operation of the motor will be explained in a non-mathematical way by the use of diagrams which illustrate its characteristics under different conditions. Only the non-synchronous type of motors will be considered, and no distinction will be made between two and three-phase motors; for, if properly designed, they are practically alike in operation.

It is necessary to understand the characteristics of the polyphase motor in order to consider properly its application to the different classes of work to be met with in practice. These characteristics can be presented in the most intelligible manner by means of curves, which represent the relations between the speed, torque or turning effort, horse power expended and developed, amperes, etc. The speed-torque curve, which represents the speed in terms of the torque, is the most important one, as upon this depends the adaptability of the motor to the various kinds of work. The starting conditions also depend upon the speed-torque characteristics. The other curves that are of importance in practice are the current, efficiency and power factor. As these are dependent, to some extent, upon the speed-torque curve, this will be considered first. Before treating of its characteristics a short description of the motor itself will be given.

Construction and Winding

The polyphase motor, like a direct-current motor, consists primarily of two parts, one stationary and the other rotating, each of which carries windings. The inside bore, or face, of the *stationery* part is generally slotted, and carries windings that resemble those of the *rotating* part, or armature of an ordinary direct-current motor without commutator. The rotating part is also slotted on its outside face, and there are windings in the slots. Both cores, or bodies, are built up of thin iron or steel plates. The general arrangement is shown in Fig. 1. One of these windings, generally that on the stationary part, receives current from a two or three-phase supply circuit. The coils of this winding, although distributed symmetrically over the entire face of the core, are really connected to form distinct groups which overlap each other. These windings form the two or three circuits in the motor. When alternating electro-motive forces are applied to these circuits, currents will flow which set up magnetic fields in the motor. These alternating fields in turn generate electro-motive forces in the windings. Part of the current flowing in the windings represents energy expended usefully, or in heating, and part serves merely as magnetizing current. The latter, like the magnetizing current of a direct-current machine, is dependent upon the dimensions of the magnetic circuit and upon the magnetic density in the various parts. Even when the motor is running with no load the magnetizing current is required.

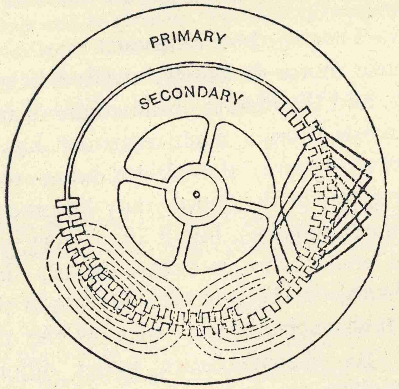


FIG. 1—ARRANGEMENT OF WINDINGS OF THE POLYPHASE MOTOR AND THE MAGNETIC FIELDS WHICH ARE PRODUCED.

The second part of the motor, generally the rotating part, receives no current from the supply circuit. The magnetic fields set up by the first set of windings pass through the second windings, and, under certain conditions, generate electro-motive forces in them. If the second windings are arranged to form closed circuits, currents will flow in them. These currents are entirely separate from those of the supply circuits.

Speed and Slip

When running, the motor has a maximum speed that is approximately equal to the alternations of the supply circuit divided by the number of motor poles in each circuit. This is the no-load speed. As the motor is loaded, the speed falls off almost in proportion to the load. The drop in speed is sometimes called the "slip." This is usually expressed in percent of the maximum speed. If, for instance, a motor has a maximum speed of 1000 revolutions and drops fifty revolutions below this at full load, it has then a slip of five percent.

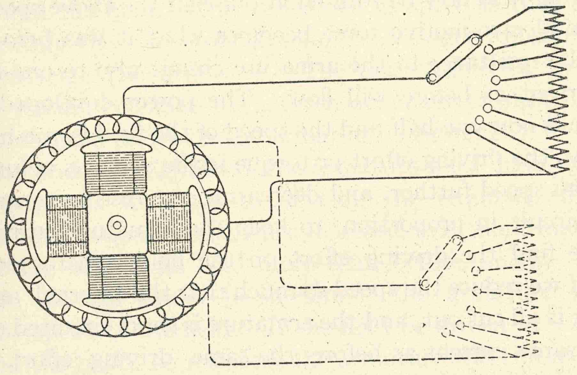


FIG. 2—DIAGRAM OF TWO-PHASE ALTERNATING-CURRENT GENERATOR, ROTATING-FIELD TYPE.

Torque and Armature Current

With this type of motor, a drop in speed is necessary for developing torque. A fairly simple illustration of this action may be obtained by considering the operating of an alternating current generator under certain conditions. We will take a type of alternator having a stationary armature and a rotatable field magnet, which can be driven at various speeds. Leads are carried out from the armature to adjustable resistances. To avoid complexity, the armature circuits and the resistances are considered as non-inductive. The field coils are excited by direct current. Fig. 2 shows this arrangement.

When the field is rotated at a certain speed, with the field coils charged, there is an alternating electro-motive force set up in the armature winding. When the armature circuit is closed through a resistance a current will flow and the armature will develop power. The power developed by the armature is slightly less than the power expended on the field shaft, which is proportional to the product of the speed and the turning or driving effort—*i. e.*, torque on the shaft. Consequently, at a given speed, a driving effort is required at the field shaft, corresponding to the power developed by the armature. If the armature current is increased or decreased, the power developed is increased or decreased also, and the driving effort will vary in proportion.

Let the field now be rotated at one-half the above speed. The armature electro-motive force becomes what it was before. Reducing the resistance in the armature circuit also to one-half, the same current as before will flow. The power developed by the armature is now one-half and the speed of the field is one-half, consequently, the driving effort or torque is the same as before. Reducing the speed further, and decreasing the resistance in the armature circuit in proportion, to keep the armature current constant, we find the driving effort on the field remains constant. Finally, if we reduce the speed so much that the external armature resistance is all cut out, and the armature is short circuited on itself with the same current as before, the same driving effort is still required.

The field is now rotating very slowly, and the alternations in the armature are very low, being just sufficient to generate the electro-motive force required to drive the armature current against the resistance of the windings. Any further reduction in speed will diminish the armature electro-motive force, and hence the armature current must fall, the power developed be diminished and the driving effort also fall in proportion. An increase in speed will increase the armature current, and thus increase the driving effort required.

If but one armature circuit is closed, the power developed will pulsate as the armature current varies, from zero to a maximum value, and the driving effort will also vary. But if the armature has two or more circuits having different phase relations, it may develop power continuously and the driving effort will then be continuous.

ILLUSTRATION OF "SLIP"

The armature has been considered as stationary and developing power while a certain driving effort was applied to the field. According to the well known law that any force is met by an opposing force, the armature must have a certain resisting effort. The armature really tends to rotate with the field, and the resisting effort is exerted to prevent this.

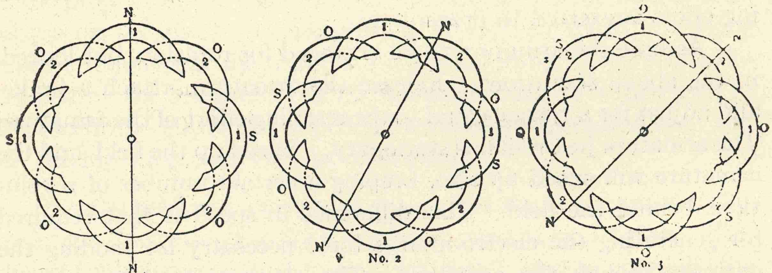
Assume the armature to be arranged for rotation, but locked, in the above operations. Release the armature, attach a brake, and adjust for a torque equal to the resisting effort of the armature. The armature just remains stationary. Speed up the field, and the armature will speed up also, keeping a certain number of revolutions behind the field. This difference in speed is that required for generating the electro-motive force necessary for sending the current through the armature. The alternations in the armature will remain constant for a given armature current, independent of the speed at which the armature is running.

If the brake be tightened, the armature must drive more current through its windings to develop the required effort, the armature alternations must hence increase, and the armature will therefore lag behind its field more than before, or the "slip" is increased. If the brake be loosened, the armature will run nearer the speed of the field. If the field be driven at a constant speed and the brake be released, the armature will run at practically the same speed as the field.

If the winding consist of but one closed circuit, the torque developed by the armature varies periodically, and that developed by the brake will vary also, but to a less extent, as it is steadied by the inertia of the rotating armature. But with two or more circuits having different phase relations, arranged for constant power developed in the armature windings, the torque developed is also constant at all times. Consequently, for constant torque at the brake, there should be two or more phases in the armature windings.

DIFFERENCE BETWEEN ILLUSTRATION AND ACTUAL CASE

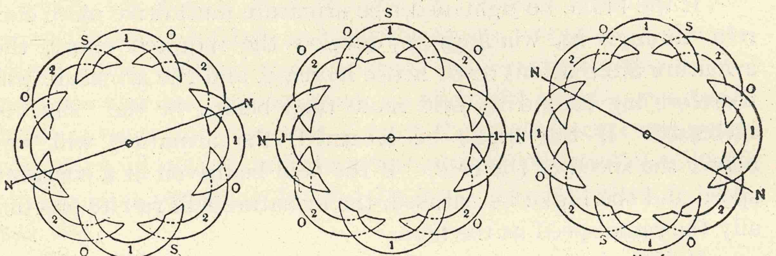
This explanation of the development of torque in the short-circuited armature is merely an attempt to illustrate certain of the actions in the polyphase motor armature by a comparison with the operations of other apparatus, that is, in general, much better understood. We cannot infer, from the above illustration, that an alternating-current generator would run as a motor under the assumed conditions, for, in the above operations, mechanical power is supplied to the field shaft, and mechanical power is delivered by the rotating armature to the brake. There is no true electro-motor action; that is, there is no transformation of electrical power supplied to mechanical power developed.



No. 1
Circuit 1 at Maximum Current
Circuit 2 at Zero Current

No. 2
Circuit 1 Decreasing Current
Circuit 2 with Increasing Current

No. 3
Circuit 1 at Zero Current
Circuit 2 at Maximum Current



No. 4
Circuit 1 Increasing in Reverse Direction
Circuit 2 Decreasing

No. 5
Circuit 1 at Maximum in Reverse Direction
Circuit 2 at Zero

No. 6
Circuit 1 Decreasing
Circuit 2 Increasing in Reverse Direction

FIG. 3—DIAGRAM SHOWING PRODUCTION OF ROTATING MAGNETIC FIELD BY TWO-PHASE CURRENTS.

The action of the short-circuited armature of the above generator and that of the polyphase motor are very similar in regard to drop in speed for developing torque. But in the polyphase motor, instead of the mechanically rotated field magnet, there is a stationary core provided with two or more windings which carry currents having different phase relation. These windings are placed progressively around the core, either overlapping or on separate poles. When the currents flow in the windings, resultant magnetic poles or fields are formed, which are progressively shifting around the axis of the motor. The closed or short-circuited armature, rotating in this field, develops torque by dropping in speed, in the same way that it developed torque with mechanically rotated field magnets. But electrical power, instead of mechanical, is now supplied to produce the shifting of rotating field, and the conversion from electrical power supplied to the field windings, to mechanical power developed by the armature shaft is a transformer action which does not appear in the above illustration.

Rotating Magnetic Field Electrically Produced

Fig. 3 shows diagrammatically a progressively shifting field, with two overlapping windings arranged for two-phase currents. Coils 1-1, etc., form one circuit, while coils 2-2, etc., form the other. Starting with the instant when the current in 1 is at its maximum value, the magnetizing force of this set of coils must be at its maximum. The current and magnetizing force of circuit 2 are at zero value. Four poles or magnetic fields, alternating N-S-N-S around the core, are formed directly over coils 1. As the current in one begins to decrease, that in 2 rises. We then have the combined magnetizing forces of the two overlapping windings. These two magnetizing forces act together at some points and oppose at others. The resultant magnetic field shifts to one side of the former position. As the current in 1 gradually falls to zero and 2 rises to its maximum value the magnetic field shifts around until it is directly over coils 2. If the current in 1 should next increase in the same direction as before, while 2 diminished, the magnetic poles would shift back again to their former position. But the current in 1, after reaching zero value, rises in the opposite direction, while that in 2 falls. This shifts the resultant poles forward instead of backward, and they gradually shift ahead until they are again directly over coils 1. But the "N" poles have shifted around until they now occupy the former position of the "S" poles. Thus, with the current in 1 passing from a maximum in one direction to a maximum in the opposite, the poles have shifted forward the width of one polar space. Current in 2 next rises in a reversed direction and the poles shift forward until, when the current in 2 is a maximum, they are over coils 2.

In the diagrams, Nos. 1, 2, 3, etc., show the positions of the shifting field under certain conditions of current in the two circuits. In No. 2, the position shown is an arbitrary one, for it depends upon the relative values of the currents in the two circuits. With the two currents equal, the position of the line N-N would be half-way between coils 1 and 2.

These diagrams show that the magnetic field due to two-phase currents in properly arranged windings shifts progressively around the axis, just as if the field were rotated mechanically.

Speed-Torque Curve

In polyphase motors, the part that resembles the field in the above description and which receives the current from the line, is usually called the primary, on account of its electrical resemblance to the primary of a transformer. The equivalent of the armature in the preceding description is called the secondary. If the alternations of the supply circuit are constant, the reversals of the currents in the field or primary will occur at a uniform rate and the magnetic field will shift around its center at a definite speed, depending upon the rate of alternation of the supply circuit and the number of poles in each circuit of the motor. If the armature or secondary rotates at the same speed as the field shifts, there will be no reversals or alternations in its magnetism, and there will be no currents and consequently, no torque. If a load is thrown on, the speed will drop and the resultant alternations in the secondary will generate electro-motive forces which will drive currents through the windings, and thus develop torque. The speed will continue to fall, and the secondary electro-motive forces will continue to increase until a torque sufficient for the load is developed.

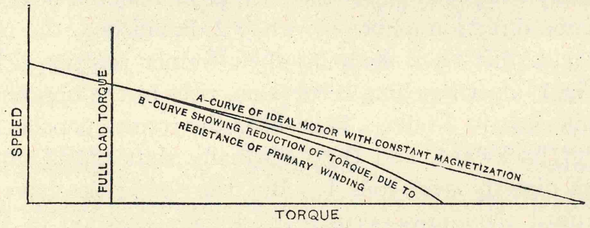


FIG. 4—SPEED TORQUE OF POLYPHASE MOTOR.

Increasing the load on the motor, the speed should fall and the torque increase until zero speed is reached. The speed-torque curve would then be of the form shown in Fig. 4, curve "A." But the shape of this curve is modified to a great extent in actual motors by certain effects which cannot be entirely eliminated.

Primary Resistance Reduces Magnetization at Heavy Loads

In the case of the revolving field, the magnetization was supposed to remain constant under different conditions. But in the motor primary, the magnetism of the primary is not constant under all conditions and it does not all pass through the secondary circuits. The primary windings necessarily have some resistance, and a certain electro-motive force is required to drive the primary current through the windings. With a constant applied electro-motive force, the primary counter-electro-motive force will diminish as the drop in primary resistance increases, and the magnetic field required will diminish also. Consequently, to develop the required secondary electro-motive force for driving the secondary current through the windings the speed must drop more than shown by curve "A" in Fig. 4. This gives a speed-torque curve as shown by curve "B," in Fig. 4. Instead of being a straight line it is somewhat curved.

Magnetic Leakage Limits Maximum Torque

But there is a still more important effect in the motor. The primary and secondary currents, and their consequent magnetizing forces, are opposed to each other. The result is that part of the primary magnetism threads across between the primary and secondary windings without passing into the secondary. Thus, the electro-motive force of the secondary is reduced, or, for a required secondary electro-motive force, the secondary alternations must be increased. This means a further drop in speed.

The secondary currents also tend to form local magnetic fields around their own coils. These local fields are alternating and set up electro-motive forces in the secondary circuits. In consequence, the electro-motive forces generated by the magnetism from the primary have to drive currents, not only against the resistance of the secondary windings, but also against these local electro-motive forces. This necessitates a further drop in speed for the required torque. These local electro-motive forces depend upon the secondary alternations and, therefore, vary with the drop in speed, and are greatest at zero speed. This introduces a very complicated condition in the secondary circuits. These magnetic fields which thread around only the primary or secondary windings are called the magnetic leakages, or stray fields, or the magnetic dispersion.

If the magnetic leakage is relatively large, that is, twenty to twenty-five percent of the total induction, and the secondary resistance is low, the speed-torque curve will have the peculiar shape shown in Fig. 5. This curve shows the torque increasing as the speed falls, until a certain maximum is reached. Beyond this point the torque diminishes with further drop in speed. If the motor is loaded to the maximum torque, a slight increase in load causes a further drop in speed, the torque diminishes and the motor stops. As a consequence, the normal rating of the motor must be considerably below this "pulling-out point." The margin necessary depends upon the nature of the load to be carried.

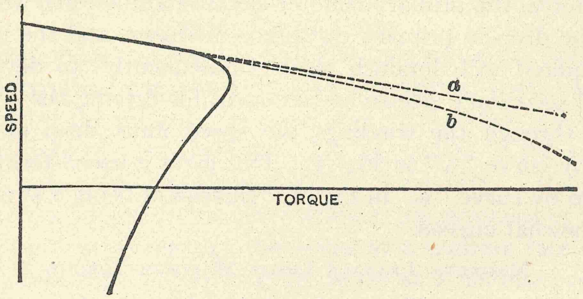


FIG. 5—SPEED TORQUE OF POLYPHASE MOTOR, SHOWING EFFECT OF MAGNETIC LEAKAGE

The starting torque, speed regulation, etc., of the polyphase motor depend upon the form of the speed-torque curves. The different methods of varying the form of these curves will be considered next.

Effect of Secondary Resistance on Speed Curve

As the secondary electro-motive force is that necessary to drive the secondary currents through the windings, it follows that the electro-motive force required must depend upon the resistance of these windings. A larger resistance means a larger electromotive force for the required current, and, therefore, a greater number of secondary alternations, or a greater drop in speed. The torque being held constant, any variation of the secondary resistance requires a proportionate variation in the slip. If the slip with a given torque is 10 percent, for instance, it will be 20 percent with double the secondary resistance, or 50 percent with five times the resistance. This is true only with the primary conditions of constant applied electro-motive force and constant alternations. The secondary resistance may be in the windings themselves, or may be external to the windings but part of the secondary body, or it may be entirely separate from the machine and connected to the windings by the proper leads.

Fig. 6 shows the speed-torque curves for a motor with different resistances in the secondary circuit. In curve "A" the secondary resistance is small. In curve "B" the secondary resistance is doubled. The maximum torque remains the same but the slip for any given torque is doubled. This motor starts much better than that in curve "A." In curve "C," the resistance is again doubled and the slip is also doubled. The starting torque is increased but the slip is rather large at the rated torque, "T." In curve "D," the slip is again doubled. In this case the torque is high at start and falls rapidly as the speed increases. In curve "E," the maximum torque is not yet reached at zero speed. Continuing these curves below the zero-speed line, that is, running the motor in the reverse direction, we get the general form of these different speed-torque curves. They are all of the same general shape, and all have the same maximum torque.

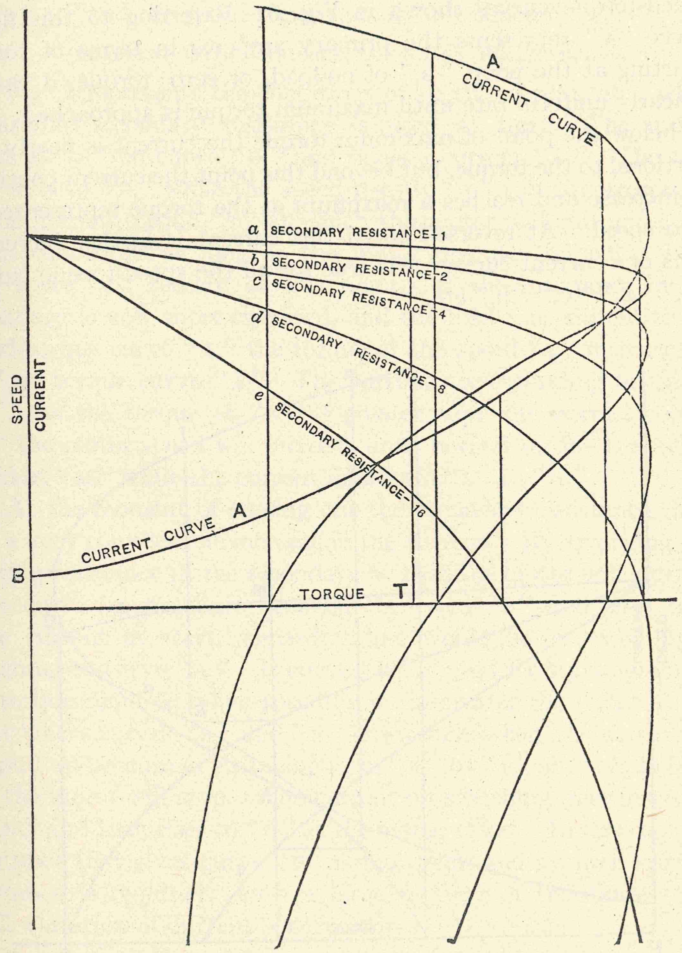


FIG. 6—SPEED-TORQUE AND CURRENT-TORQUE CURVES OF POLYPHASE MOTOR WITH SECONDARIES OF DIFFERENT RESISTANCE

So far as torque is concerned, curve "D" is the best for starting. But for running, curve "A" gives the least drop in speed. Consequently, if a resistance is introduced at start that will give the speed-torque curve "D," it should be cut out or short-circuit for the running condition. This is one method of operation that has been much used.

CURRENT CURVE

In determining the best starting condition, the current supplied to the primary must be considered in connection with the speed-torque curves. This current is plotted with the series of speed-torque curves shown in Fig. 6. Referring to this figure, curve "A" represents the primary amperes in terms of torque. Starting at the point "B," of no-load, or zero torque, it rises at a nearly uniform rate until maximum torque is approached; that is, below the point of maximum torque the current is nearly proportional to the torque, but beyond this point the current continues to increase and reaches a maximum at the torque represented by zero speed. At reversed speed this current is further increased. This one current curve holds true for all the speed-torque curves, "A," "B," "C," "D," etc.

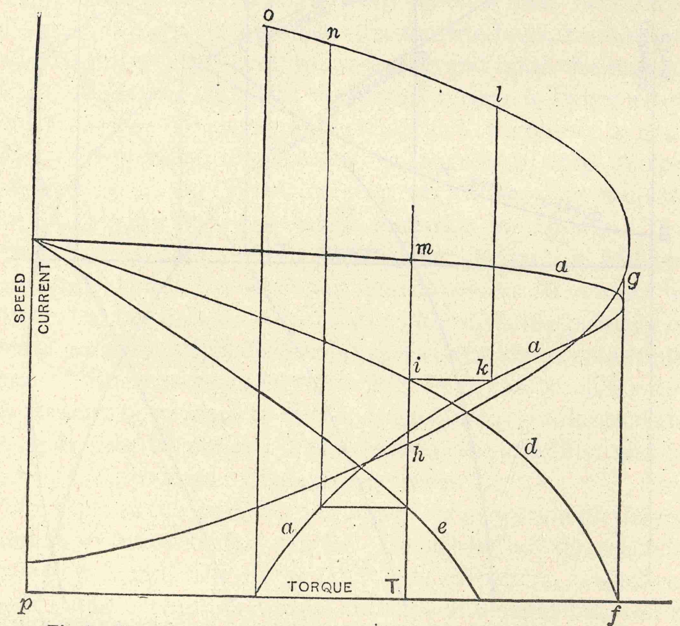


Fig. 7—STARTING CONDITIONS WITH VARIABLE SECONDARY RESISTANCE

Comparing the different curves, we see that "A" takes the most current at start, and gives low torque; "B" takes less current than "A," and gives more torque; "C" takes less current than "B"; "D" takes less current than "C" and gives the maximum torque at start; "E" takes less current than "D," and develops less torque; but the current and torque are very nearly in proportion over the whole range. From this we see that a speed-torque curve of the form of "D" or "E" is decidedly better for starting than "A" or "B." But for running at less than the maximum torque there is no advantage, so far as current is concerned, in curve "D" over curve "A," and the speed regulation of "D" is poor.

STARTING WITH VARIABLE SECONDARY RESISTANCE

Fig. 7 represents the conditions of speed, current, etc., when a variable secondary resistance is used at start. The motor starts at "F" on curve "D," and takes a current "G." The current falls to "H," while the speed rises to "I," which corresponds to the normal torque "T" at which the motor will run under the given conditions as long as the motor operates on curve "D." The speed will remain at this point. If the resistance in the secondary is now short-circuited, and the load thus shifted to the speed-torque curve "A," the torque at the speed "I," increases to "K" on torque curve "A." The current corresponding to this is "L." As the torque at "K" is greater than the normal torque "T," the motor speed will increase until normal torque is reached again at "M," while the current falls from "L" to "H."

At the moment of cutting out the secondary resistance there was a very considerable increase in the current. By arranging the starting resistance in the secondary so that the motor will start at some curve intermediate between "A" and "D" and thus take more current at start, somewhat less would be required upon switching to curve "A." If curve "E" is used for starting, and if the torque required when speeding up is greater than that at the point where curves "A" and "E" cross each other, the motor will not pull up because in switching from "E" to "A," the torque falls, and the motor will stop. The current on switching over increases to "N," and then rises to "O" as the motor stops. In this case the resistance that gives curve "E" is too great, and a lower starting resistance is required; with a large number of resistance steps small variation of current is secured.

By making several steps of the secondary resistance, so that it may be cut out gradually, the motor may be made to pass through a series of speed-torque curves with much smaller variations of current than shown in the preceding diagrams. This method has been used to some extent, but requires collector rings or a complicated switching arrangement in connection with the motor secondary.

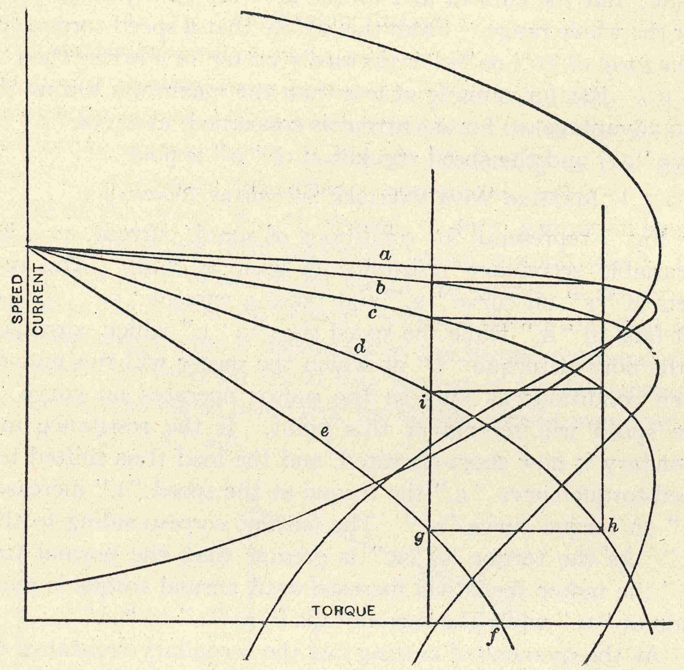


FIG. 8—STARTING CONDITIONS WITH FIVE SECONDARY RESISTANCE STEPS.

Fig. 8 shows the conditions for starting and speeding up with five speed-torque curves. The motor starts on curve "E" at "F." The speed rises to "G." The motor is then switched to curve "D," the torque rising to "H." The speed then rises to "I." In this way the motor passes successively from "D" to "C," "B" and "A," until the full speed is reached. The currents at no time reach very high values.

Plotting the current in terms of speed, the use of a large number of steps is shown to better advantage. This is shown in Figs. 9 and 10. Fig. 9 shows the same starting conditions as Fig. 7 with curves "D" and "A." The current starts at "A" and falls to "B." The resistance is then short-circuited and the current rises to "C" and then falls to "D," which is the same as "B." If "A" had been higher at start, "C" would have been lowered slightly. But as the time required for passing from "A" to "B" is generally greater than that from "C" to "D," "C" may be higher than "A." If the motor is not required to develop such a large torque when pulling up, then "C" may be lowered while "A" is left unchanged.

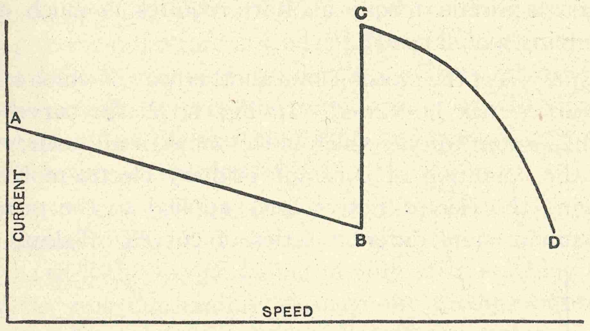


FIG. 9—CURRENT SPEED CURVE FOR MOTOR STARTING, AS IN FIG. 7.

In Fig. 10, the currents in terms of speed are shown for five steps with the five speed-torque curves of Fig. 8. The starting current "A" is low, and none of the currents, when switching from one curve to another, is large. The dotted lines show the corresponding currents for two steps, as in Fig. 9.

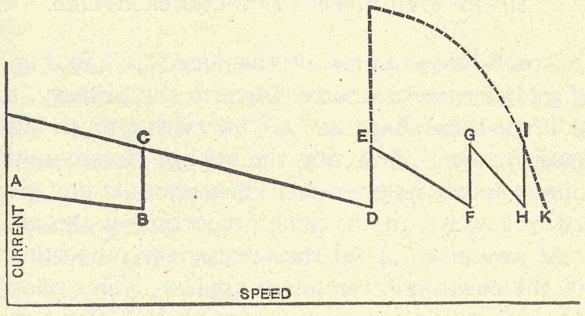


FIG. 10—CURRENT SPEED CURVE FOR MOTOR STARTING, AS IN FIG. 8. DOTTED LINES SHOW SAME CURVE AS FIG. 9.

MOTORS FOR VARIABLE SPEED WORK

For variable speed work, such as cranes, elevators, etc., the series of curves in Fig. 6 shows one method of regulating the speed. By varying the secondary resistance over a wide range, any speed from zero to maximum may be obtained with any torque up to the maximum. This requires the use of collector rings and adjustable rheostats. The variations in speed are obtained by wasting energy in resistance. For a given torque the same power is expended on the motor whether the speed is zero or maximum. To obtain a certain torque at start requires as much power as when running at full speed.

An analysis of the motor shows another way in which the speed-torque curves may be varied. In Fig. 6, all the curves show a certain maximum torque which is the same in all cases; but this is with the condition of constant primary electro-motive force. By varying the electro-motive force applied to the primary we may obtain a quite different series of curves. Taking, for example, a speed-torque curve of the form "A" in Fig. 11, and applying a higher electro-motive force to the primary, a curve is obtained of the same shape as "A," but with a much higher point of maximum torque. Lowering the applied electro-motive force, the maximum torque is lowered. The torques at any given speed are raised or lowered in the same proportion as the maxima are varied. At any given speed the torques are proportional to the square of the electro-motive forces applied. This relation holds good for any form of the torque curve, whether of the shape "A," "D," or "E," shown in Fig. 6.

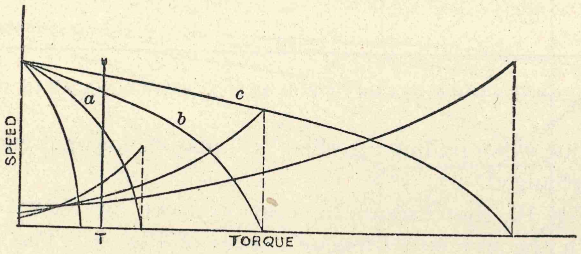


FIG. 11—SPEED-TORQUE AND CURRENT-TORQUE CURVES FOR POLYPHASE MOTOR WITH DIFFERENT VOLTAGES APPLIED.

The current curves are also shown in Fig. 11. They all have the same general shape, but have different maximum values, these being proportional to the electro-motive forces applied. The speed-torque curve "A" in Fig. 11 has the same shape as "D" in Fig. 6, which gave too great a drop in speed. In Fig. 11, curve "B," which is the same form as "A," gives less speed drop for the same torque. Curve "C" gives less than "B," and has fairly good speed regulation from no-load up to normal torque "T." But this result is obtained at the expense of increased induction in the iron, and large no-load or magnetizing current due to the higher electro-motive force, is required. If it is possible to obtain a speed-torque curve like "C" in Fig. 11 with the normal electro-motive force applied, we can obtain good speed regulation from no-load up to the rated torque, and shall be able to start the motor with the maximum torque it can develop. Then, by lowering the applied electro-motive force, the same form of speed-torque curve will be retained, but the starting torque and starting current may be lowered to any extent desired.

VARIABLE SPEED BY VARYING VOLTAGE

Returning to Fig. 5, it was stated that the peculiar shape of this curve, with the torque falling rapidly after reaching a maximum value, was due mainly to magnetic leakage between the primary and secondary windings. But if the motor is so proportioned that the leakage is very small compared with the useful field, the speed-torque curve takes a quite different shape. The maximum torque is increased directly as the magnetic leakage is diminished. This is shown in Fig. 12. Here "A" is similar in shape to curve "A" in Fig. 6; "B" represents the speed-torque curve with the magnetic leakage reduced one-half; "C" represents it with about one-half the leakage of "B," and "D" with one-half that of "C."

In comparing Figs. 6 and 12, it may be noted that "A" in one is the same form as "A" in the other, although drawn to a different scale. In Fig. 12, "B" has the same shape as in Fig. 6, but has a different maximum value. The same is true of curves "C" and "D" in the two figures. By lowering the applied electro-motive forces for curves "D," "C" and "B" of Fig. 12, so that the maximum torques are equal to that of "A," as shown by the dotted curves, we get practically the same curves as in Fig. 6.

Curve "D," in Fig. 12, gives as good running conditions as curve "A" in Fig. 6, having about the same drop in speed at the normal torque "T." We have, then, in "D" a curve which starts at the point of maximum torque, and which also has a small drop in speed at the normal load. The objection to this curve is that the starting current and starting torque, although in the proper proportion to each other, are both much greater than is necessary or desirable. By reducing the applied electro-motive force at start, however, lower torques and currents are obtainable. In this way we may combine good starting and running conditions in one motor without the use of starting resistances, and with a secondary that has no resistance except that of its own windings. Fig. 13 shows the speed-torque and current curves of such a motor with the applied electro-motive force varied over a considerable range.

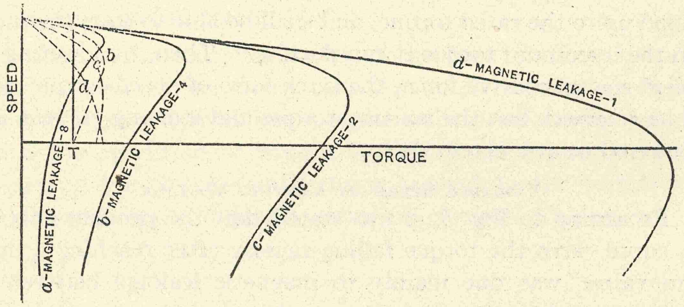


FIG. 12—SPEED-TORQUE CURVES OF POLYPHASE MOTOR SHOWING EFFECT OF MAGNETIC LEAKAGE. DOTTED LINES SHOW CURVES b, c, d WITH REDUCED VOLTAGE

If but one electro-motive force is desired for starting and speeding up, and the motor is then to be transferred to the working electro-motive force, the speed-torque curves should preferably

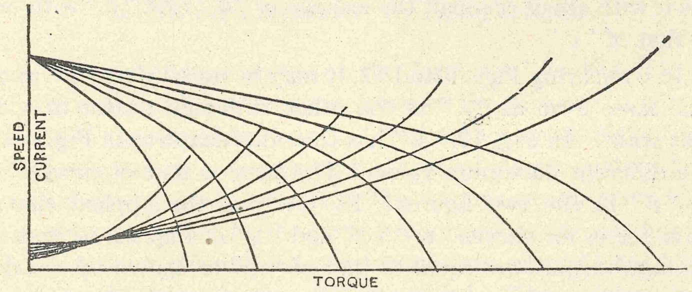


FIG. 13—SPEED-TORQUE AND CURRENT-TORQUE CURVES FOR POLYPHASE MOTOR WITH ELECTRO-MOTIVE FORCE VARIED OVER A WIDE RANGE.

have the shape shown in Fig. 14. The motor starts with the desired torque at reduced e. m. f., and comes up to almost rated speed before switching over. This is suitable for constant speed work. In Fig. 14 are shown both the starting and running speed-torque curves, and the currents both in the motor and the line. The line currents are smaller than the motor currents in the ratio of reduction of electro-motive force in the regulating transformers.

Speed-Torque Curves for Variable Speed Work

For cranes, elevators, and variable speed work in general, curves of the form shown in Fig. 15 are preferable. The line currents are also shown in this figure. This series of speed-torque curves shows that a wide range of speed may be obtained by proper variations of the applied electro-motive force. The line currents "A," "B," etc., practically overlap each other. This means that the line current required with this method of control is very nearly constant for any given torque, independent of the speed. The same is true of the method of control by varying the secondary resistance. It may be noted that the current for starting, as on curve "C," for instance, is slightly greater than that required for running at the same torque on "B" or "A." This is due to the speed-torque curve being somewhat curved at its outer end. With a somewhat higher resistance of the secondary the curves are more

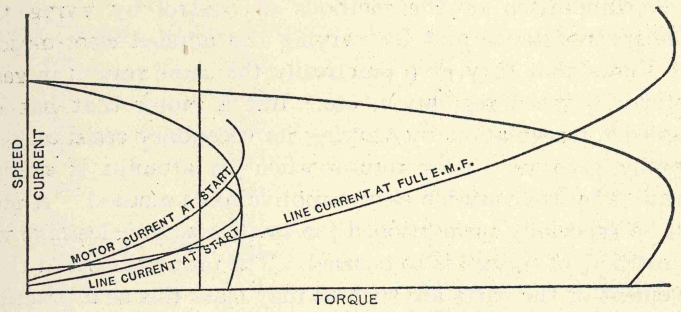


FIG. 14—BEST SHAPE OF SPEED-TORQUE CURVE FOR MOTOR STARTED AND SPEEDED UP WITH A SINGLE REDUCED VOLTAGE, BEFORE BEING TRANSFERRED TO WORKING VOLTAGE.

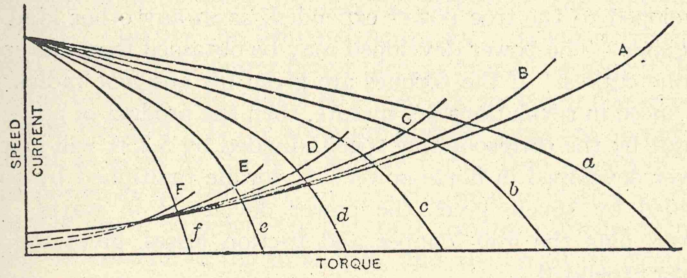


FIG. 15—SPEED-TORQUE AND CURRENT-TORQUE CURVES OF MOTOR FOR CRANES, ELEVATORS AND SIMILAR VARIABLE SPEED WORK WITH VOLTAGE CONTROL. CURVES a, b, c, d, e, f, ARE SPEED-TORQUE CURVES WITH VARIABLE VOLTAGE. CURVES A, B, C, D, E, F, SHOW CORRESPONDING LINE CURRENT.

nearly straight, but the drop in speed is somewhat increased on the speed torque for any given electro-motive force. In practice, a compromise is made between the best possible starting condition and a condition of less speed drop.

A comparison of the methods of control by varying the secondary resistance and by varying the applied electro-motive force shows that they give practically the same results in regard to starting, speed regulation, etc. But a motor that has been designed for regulation by varying its secondary resistance, will generally give very poor results when an attempt is made to operate it by the variable electro-motive force method. A motor must be especially proportioned for small magnetic leakage when this method of control is to be used. The proportions and the arrangement of the parts are such as may class this as a practically distinct type of motor.

Efficiency and Power Factor

We come now to the other characteristics of the polyphase motor, the most important of which are the efficiency and the power factor. The importance of efficiency is generally appreciated, but the question of power factor in most cases appears to be not thoroughly understood or else is entirely overlooked.

The efficiency of a polyphase motor is the ratio of the power developed to the true power expended, as in any other kind of a machine. The power developed may be obtained from the speed-torque curves. If the torques are given for one foot radius, and the speed in revolutions per minute, then the product of any given torque by the corresponding speed, divided by 5,250, will give the power developed in horse-power; or torque multiplied by speed, divided by seven, gives the power developed in watts. This power, plus the iron, copper and friction losses, gives the true power expended.

The power factor is the ratio of the true power to the apparent power expected. This apparent power is proportional to the products of the primary currents by the electro-motive forces. If there is magnetizing current, and if the motor has magnetic leakage, the primary currents are not in phase with their electro-motive forces and their products represent anapparent power which is greater than the true energy expended. The current of each circuit can be considered as made up of two currents, one of which is in phase with the applied electro-motive force, representing true energy, and the other at right angles to the electro-motive force, representing no energy. The right-angled component is the one that has an injurious effect on the regulation of the generator, transmission lines, transformers, etc.

The size of this component, compared with the useful current, may be shown by a table:

Power Factor	Total Current	Useful Component	90 Degree Component
100	100	100	0.
99	100	99	14.2
98	100	98	19.9
95	100	95	31.2
90	100	90	43.6
80	100	80	60.0
70	100	70	71.4
60	100	60	80.0
50	100	50	86.6
40	100	40	91.6

Effects of Lagging Current

At 90 percent power factor, for instance, the current that is lagging 90 degrees behind the electro-motive force is equal to 43.6 percent of the total current flowing. This lagging current reacts on the generator, affecting the regulation. In an alternating-current generator, a 90-degree lagging current in the armature coils directly opposes the field magnetization. When delivering a current at 90 percent power factor there is over 43 percent of this current opposing the field, and at 80 percent power factor 60 percent is opposing the field. If the armature ampere turns are normally 20 percent as great as the field ampere turns, then a load of 80 percent power factor will give an opposing magnetization in the armature of about 60 percent of the total armature ampere turns, or about 12 percent of the total field, and the armature electro-motive force will be lowered approximately that percent more than with a load of 100 percent power factor.

The inductive effects of the lagging current in the transmission circuits and transformers are much more serious than those from a current that is in phase with the electro-motive force. The generator, transformers, lines and motors also have increased losses, due to the large current required when the power factor is low. An 80 percent power factor in a system means losses due to heating of conductors more than 50 percent greater than those with 100 percent power factor. These figures indicate the importance of good power factors in an alternating-current system.

MAGNETIZING CURRENT AND MAGNETIC LEAKAGE DETERMINE POWER FACTOR

The lagging, or 90-degree component, of the current in a motor depends upon the amount of the no-load, or magnetizing, current and upon the magnetic leakage. Let this lagging component be expressed in percent of the total current. Also express the magnetizing current in percent of the total current, and the total magnetic leakage in percent of the total primary induction. Then the sum of the percents of magnetizing current and magnetic leakage represents very closely the percent of the lagging component of the primary current. If, for example, the magnetizing current is 30 percent and the leakage is 14 percent, the resulting lagging component is about 44 percent. From the preceding table, this indicates about 90 percent power factor. A low leakage and a high magnetizing current may give the same power factor at full load as a high leakage and low magnetizing current; but at half load, the percent magnetizing current is practically doubled, while the percent magnetic leakage is halved. Hence, a low magnetizing current is of great importance in maintaining a high power factor. If a high value of power factor over a wide range is desired, then both the leakage and the magnetizing current must be low.

VOLTAGE CONTROL VERSUS RHEOSTATIC CONTROL

The method of control by varying the primary electro-motive force is dependent upon the fact that the motor has a low magnetic leakage. By using certain proportions and arrangements of the windings on the primary and secondary, the magnetizing current may be made comparatively low. Thus both conditions for good power factor are obtained.

With the method of control by varying the secondary resistance, good power factors may be obtained. But the form of secondary winding required when variable resistances are used tends to reduce both the power factor and the maximum torque.

BEST FORM OF SECONDARY WINDING

An elaborate series of tests was made to determine the best type of winding for the secondary of a polyphase motor. First, two circuits were arranged to give secondary phases ninety degrees apart. The starting, running and maximum load conditions were determined. Then a three-phase secondary winding was used. This gave a higher pulling-out torque and better power factor than the two-phase. Four phases were tried and were better than three; and six were better than four. Then twelve phases were tried, with a gain over six in maximum torque, but not much gain in efficiency. The power factor was somewhat improved. Finally the winding was completely short-circuited on itself, all coils being connected to a common ring. This gave a further increase in maximum torque and power factor over the preceding arrangement, but there was very little gain in efficiency. The same primary was used in all these tests. Each time the number of secondary circuits was increased the power factor was somewhat improved. This was due to the fact that the secondary currents were able to so distribute themselves that the local electro-motive forces in the coils, due to leakage, were diminished; or, the magnetic leakage may be considered to have been diminished. This would necessarily give higher pulling-out torques and higher-power factors.

BEST FORM OF PRIMARY WINDINGS

Very complete tests were also made to determine the best form of primary winding, and a certain method of distribution of the coils was found to diminish the primary magnetic leakage very considerably. This somewhat increased the maximum torque and the power factor. Utilizing the arrangements of the primary and the secondary windings just described, and otherwise proportioning for small magnetic leakage, a motor may be obtained that has a comparatively low total induction, and yet has a magnetic leakage of but a few percent. The low induction allows a small magnetizing current and comparatively low iron losses. The low leakage gives a high pulling-out torque, and thus allows a good speed regulation, and also good starting conditions, by varying the applied electro-motive force.

TYPE C MOTORS

Motors that are adapted for operation under the conditions of variable applied electro-motive forces with constant secondary resistance must have the special forms of speed-torque curves shown in Figs. 12 to 15, and they may therefore be considered as forming a distinct type. This type has received the name Type C. The Type C motor is always characterized by low magnetic leakage and consequent high pulling-out torque. The secondary has no adjustable resistance and all regulation is obtained by varying the adjustable electro-motive force. The secondary is made the rotating part, on account of the type of winding used, which consists of copper bars placed in tunnels or slots in the core and bolted to two end rings. There are no bands, and the question of insulation is of very little importance for the maximum secondary electro-motive force does not exceed three volts in a 500 horsepower motor and is less with smaller sizes.

Advantages of Type C Motors

This type of motor possesses several distinct advantages over other forms of polyphase motors. The method of control, by varying the electro-motive forces applied to the motor, leads to two very important advantages, one of which is mechanical and the other electrical. With this method of control there are no regulating appliances on the motor and, in consequence, it may be of the simplest possible form. The electrical advantage is that the motor may be started and controlled from a distance. Thus it may be placed entirely out of reach of the operator. On traveling cranes, for example, this is of special advantage, for in this case only the primary wires need be run from the operator's cage to the motor. If there are several motors on the crane, there may be one wire common to all the motors and but two additional wires per

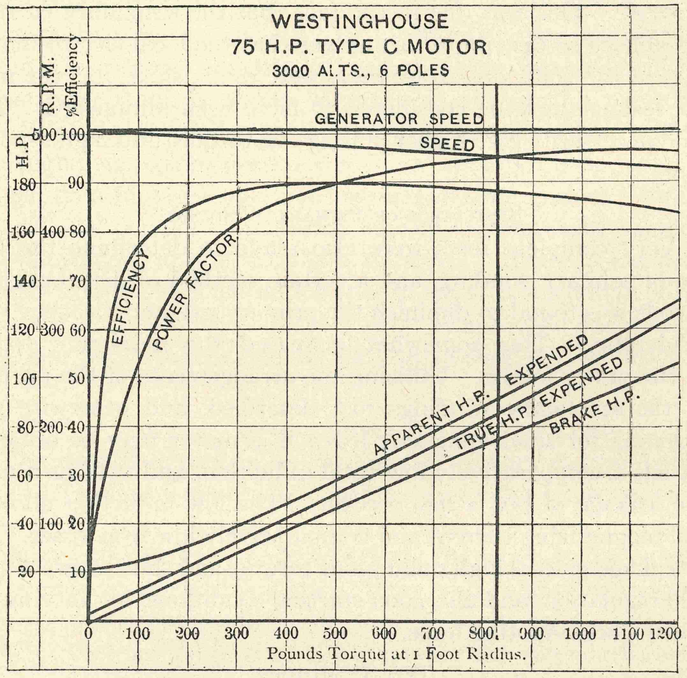


FIG. 16—PERFORMANCE CURVE OF 75 H. P. TYPE C MOTOR

motor are required. Thus for the three motors, a minimum of eleven trolley wires may be used.

If the variable electro-motive forces are obtained from transformers, the switches for operating several motors may be wired to one set of transformers and the motors may be started and regulated independently. For traveling cranes, only one set of transformers is used for the hoisting, bridge and traveling motors, and this set may supply currents at different electro-motive forces to all the motors at the same time. A further advantage possessed by this motor lies in the high pulling-out torque. If a heavy overload, or a load having great inertia, is suddenly thrown on a motor that has a speed-torque curve like "A" in Fig. 6, the point of maximum torque may be passed for an instant, and the motor will be stopped unless the load is quickly removed. A Type C motor in this case would have its speed pulled down for a moment, but this reduction in speed gives an increased torque, thus enabling the motor to carry the overload.

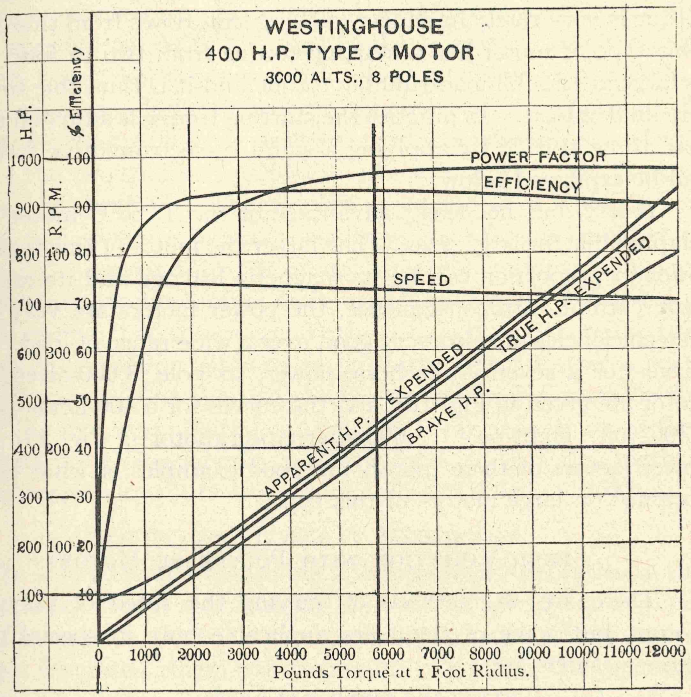


FIG. 17—PERFORMANCE CURVES OF 400 H.P. TYPE C MOTOR

If the electro-motive force of the system is suddenly lowered, the pulling-out torque of the motors is lowered very materially. A reduction of twenty percent in the electro-motive force will lower the pulling-out torque to about two-thirds of its former value. Even with a temporary drop in the electro-motive force, such as would be caused by a momentary short-circuit on the lines, this may be sufficient to stop the motor. But a motor that has a pulling-out point several times as large as its normal running torque is very rarely in danger of being shut down from this cause. This type of motor has a starting torque from two to four times as large as the full-load running torque and it is thus able to start any kind of load. In practice the starting torque is adjusted to the load to be started by applying a suitable electro-motive force, as will be explained below.

A last, but not least, advantage of the Type C motor is its adaptability for large sizes. The larger the motor of this type, the lower in proportion can be its magnetic leakage and its magnetizing current. In consequence, the power factors are very high. The efficiencies are also very good over a wide range of load. The curves for a seventy-five horse-power, six-pole, 3,000-alternation motor are given in Fig. 16; also the curves for a 400-horse-power, 2,300-volt, eight-pole, 3,000-alternation motor in Fig. 17. The power factors of these motors are good examples of what can be obtained on large motors of this type.

Speed Variation with Polyphase Motors

There are six methods of varying the speed of polyphase motors, but some of them are applicable only in special cases. These methods are:

(1)—Varying the number of poles.
(2)—Varying the alternations applied.
(3)—Motors in tandem, or series-parallel.
(4)—Secondary run as single-phase.
(5)—Varying the resistance of the secondary.
(6)—Varying the electro-motive force of the primary, with constant secondary resistance.

Some of these methods are efficient, while some are very inefficient if the speed is to be varied over a wide range.

Varying the Number of Poles

The first method, varying the number of poles, is efficient to a certain extent, but is limited in the number of combinations of

poles obtainable. But if combined with some of the other methods it may be made fairly effective over a wide range. It consists in varying the arrangement of the primary coils in such a way that the number of resulting poles is varied. This may be accomplished by having two or more separate windings on the primary; or one winding may be used, it being rearranged for different speed. With this method of varying the speed, a secondary of the "cage" type is the only practical one. With a "grouped" or "polar" winding on the secondary, this would need rearranging for the different speeds, just as in the case of the primary. But the cage winding, being short-circuited on itself at all points, is adapted to any number of poles. In general, this method of regulation will allow for only two speeds without great complications, and the ratio of the two speeds is preferably two to one, although three to one may be obtained. The simplest arrangement of winding consists of two separate primary windings; one for one number of poles, and the second for the other. In combination with a variable primary electro-motive force, the speed-torque curves being of such shape that this method may be used, the variable-pole method of regulation may be made fairly efficient over a wide range of speed. But the two windings considerably increase the size of the motor, while the one-winding arrangements are rather complicated. Consequently, we may consider that this method of speed variation will be used only in special cases.

Varying the Number of Alternations

The second method, variable alternations, is theoretically the ideal method; but it is practically limited to a few special applications, for we have as yet no commercial alternation transformer.

In a few cases, where but one motor is operated, the generator speed may be varied. If the generator is driven by a water-wheel, its speed may be varied over a wide range, and the motor speed will also vary. If the generator field be held at practically constant strength, then the motor speed may be varied from zero to a maximum at constant torque with a practically constant current. This is a convenient method of operating a motor at a distance from the generator. The speed of the motor may be completely controlled by an attendant at the generating station.

Fig. 18 shows the speed-torque and other curves of a motor when operated at 7200, 3600, 1800 and 720 alternations per minute, or at 100, 50, 25 and 10 percent of the normal alternations. The speed-torque curves, corresponding to the above alternations are, “a,” “b,” “c” and “d.” The current curves are “A,” “B,” “C” and “D.” This figure shows that for the rated torque “T,” the current is practically constant for all speeds, but the electro-motive force varies with the alternations. Consequently, the apparent power supplied, represented by the product of the current by electro-motive force, varies with the speed of the motor, and is practically proportionate to the power developed.

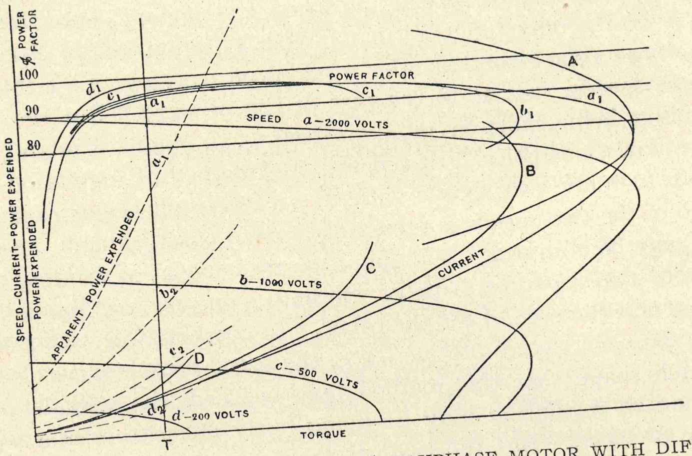


FIG. 18—PERFORMANCE CURVES OF POLYPHASE MOTOR WITH DIFFERENT ALTERNATIONS AND ELECTRO-MOTIVE FORCES.

Motors in Tandem or Series-Parallel

The third method is to run motors in tandem or series-parallel. In this arrangement, the secondary of one motor is wound with a grouped or polar winding to give approximately the same electro-motive force and number of phases as the primary. The secondary is connected to the primary of a second motor. The secondary of the second motor may be closed on itself, with or without a resistance, or may be connected to the primary of a third motor, etc. The arrangement with two motors is shown in Fig. 19. At start, motor No. 1 receives the full number of alternations on its primary, and its secondary delivers the same number to the primary of motor No. 2. Both motors will start. As motor No. 1 speeds up, its secondary alternations fall. At about one-half speed, its secondary alternations are about one-half its primary, and motor No. 2 receives one-half the alternations of motor No. 1; it also tends to run at half-speed. Therefore, if both motors are coupled to the same load, this half speed is a position where the two motors tend to operate together. By connecting both primaries across the line, both motors will be run at full speed. Thus, with two motors, two working speeds may be obtained. This method always requires at least two motors. Its application is limited to a few special cases.

Secondary With Only a Single Circuit Closed

The fourth method—the secondary run with a single circuit closed—will give a half-speed, and with two or more circuits closed, will give full speed. But the power factor at the half-speed is very low, and the efficiency is not nearly so good as when run at full speed. This may have a few special applications. Fig. 20 shows this arrangement.

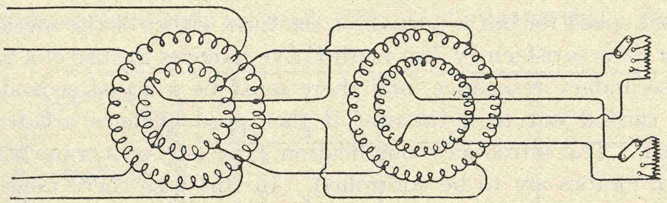


FIG. 19—DIAGRAMMATIC ARRANGEMENT OF THE TWO POLYPHASE MOTORS CONNECTED IN TANDEM OR SERIES PARALLEL

Varying the Resistance of the Secondary

The fifth arrangement is by varying the resistance in the secondary. This method was considered before when the speed-torque characteristics were shown. This will not give constant speed except with constant load, as the speed-torque curve, with a relatively large resistance is a falling curve. At heavy torques, the motor will run at very low speeds, while with light loads it will run at almost full speed. The speed regulation will be similar to that of a direct-current shunt motor with a resistance in circuit with the armature. To hold constant speed with variable load, this resistance requires continual adjustment.

Varying Primary Voltage

The six method—that in which the primary electro-motive force is varied while the secondary resistance is held constant—gives the same results as the fifth method, as the speed-torque curves are similar. To hold a constant low speed, the electro-motive force must be varied continually if the load is changing.

Like the fifth method, it is not efficient at low speeds, as the reduction in speed is obtained by means of a corresponding loss of energy in the secondary circuits.

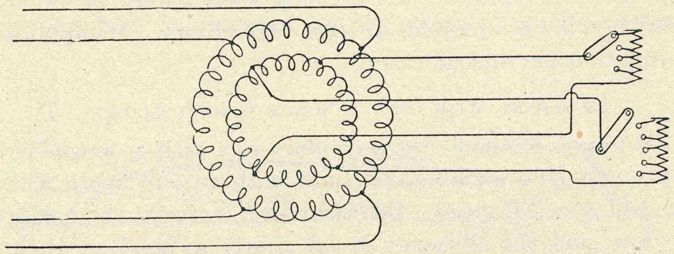


FIG. 20—POLYPHASE MOTOR WITH ONLY ONE SECONDARY CURRENT CLOSED.

For crane work, hoisting, etc., where it is necessary to run at reduced speed for but a portion of the time, either of the methods five or six is satisfactory, but method five requires the use of a variable secondary resistance, and there must be a set of secondary leads carried out to a rheostat if the speed changes are to be gradual. This introduces complication, especially on a crane where several motors are to be controlled. In this case there must be trolley wires for both the primary and the secondary circuits of each motor. But by method six, the control is effected in the primary circuit and only primary trolley wires are needed, and these may be controlled from one pair of transformers, as explained before. The sixth method is therefore the simplest and most practical one to use for hoisting, etc., and will be found to present many advantages for all classes of work, whether speed regulation is important or not.

Method of Varying Primary Electro-Motive Force

There are several methods of varying the electro-motive force applied for starting and varying the speed on the Type C motor. These may be classified under three headings:

(1)—Varying the electro-motive force from the generator.
(2)—Varying the electro-motive force by transformers.
(3)—Varying the motor connections.

Varying Electro-Motive Force from the Generator

A variable electro-motive force may be obtained from the generator in several ways. The generator may be run at low

speed, with the field charged. This gives lower electro-motive force and lower alternations at the same time. This is adapted only to places where all the motors are to be started at once.

The generator may be run at normal speed and its field charge lowered. This gives the normal alternations with lower electro-motive force. This is practicable only where all the motors are to be started at once.

A third method is to so arrange the generator windings that two or more electro-motive forces for each phase may be obtained. A lower electro-motive force may be used at start, and a higher for running.

The different arrangements of the generator windings for this purpose are as follows:

If the armature has but one winding closed on itself, like a direct-current machine, two or three phases may be taken off. For two phases four leads are used. Fig. 21 illustrates this. Between

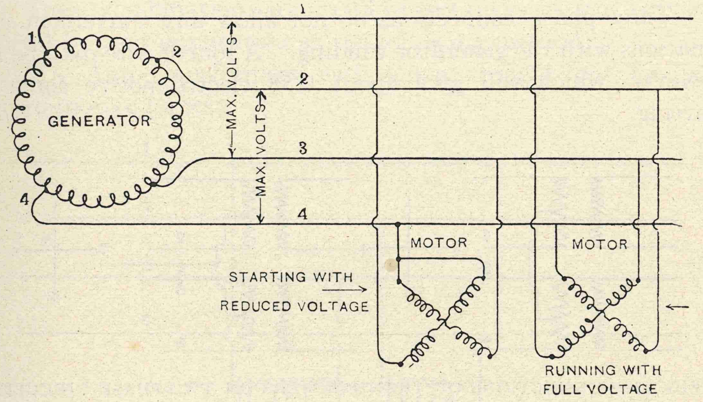


FIG. 21—CONNECTIONS FOR TWO-PHASE MOTORS STARTING ON SIDE CIRCUITS.

1-3 and 2-4 is the maximum electro-motive force, and between 1-2, 2-3, 3-4 and 4-1 there is 0.7 the electro-motive force of 1-3. The electro-motive force 1-2 is at quarter phase to that of 4-1 and 2-3, and the electro-motive force 3-4 is at quarter phase to that of 2-3 and 4-1. Therefore, across any two adjacent side circuits we have quarter phase circuits of 0.7 the electro-motive force of the main circuit. A motor may thus be started on any adjacent side circuit and then switched to the main circuit. This method is well adapted for local plants where the generator electro-motive force is 200 or 400 volts. If there are many motors to be started, and the starts are numerous, it is advisable to wire the starting switches so that the various motors are started on different side circuits.

If the generator winding is of the "open coil" type, a similar arrangement may be obtained for two phases. The two windings may be connected to the middle point, thus giving side circuits of 0.7 electro-motive force. This is shown in Fig. 22.

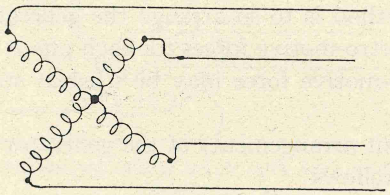


FIG. 22—WINDINGS OF "OPEN COIL," TWO-PHASE GENERATORS CONNECTED TOGETHER AT MIDDLE POINT TO ALLOW STARTING OF MOTORS FROM "SIDE CIRCUITS".

Three-phase connections do not allow any convenient combinations with the generator winding. A fourth wire may be run, however, which will give about 0.58 electro-motive force for starting.

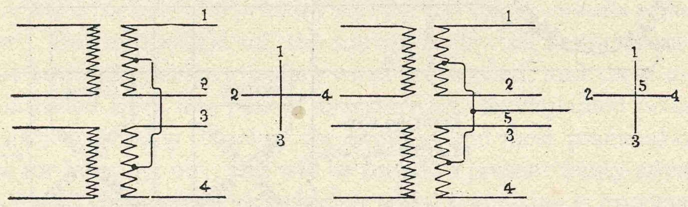


FIG. 23—CONNECTIONS OF TRANSFORMERS ON TWO-PHASE CIRCUITS TO GIVE .7 AND .5 NORMAL VOLTAGE FOR STARTING MOTORS.

Variable Electro-Motive Force from Transformers

The method of varying the electro-motive force by means of transformers admits of many different combinations. Several of the simpler forms will be given.

(1) The transformers may be so connected that two or more electro-motive forces may be obtained.

For two-phase circuits, the secondaries may be connected together at the centre, as shown in Fig. 23. This gives two main circuits, and four side circuits of lower electro-motive force. If an extra wire be carried out from the point 5, then 1-5, 2-5, will form a two-phase combination for 0.5 voltage, while 1-2, 2-3 form a two-phase combination for 0.7 voltage, and 1-3 and 2-4 give full voltage.

Another method is to connect the secondaries at one side of the centre, as shown in Fig. 24. Then 3-5 and 4-5 give one electro-motive force; 1-5 and 2-5 give a higher electro-motive force, and 1-3 and 2-4 give full electro-motive force.

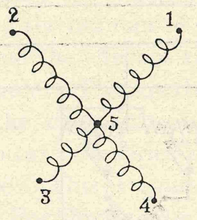


FIG. 24—CONNECTIONS OF SECONDARIES OF TRANSFORMERS ON TWO-PHASE CIRCUIT AT A POINT ONE SIDE OF THE CENTER, TO OBTAIN LOWER ELECTRO-MOTIVE FORCES FOR STARTING MOTORS.

These combinations are useful in certain cases, but are not as general in their application as the following method:

(2) Auto-transformers with loops brought out for lower electro-motive forces.

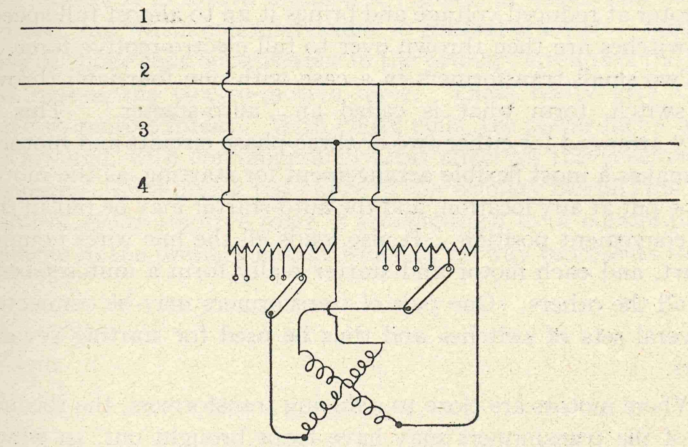


FIG. 25—DIAGRAMMATIC ARRANGEMENT OF AUTO-TRANSFORMERS AND CONTROLLERS FOR REGULATING SPEED OF TWO-PHASE MOTOR BY VARIANCES OF VOLTAGE.

In this method, no special combinations of the lines, lowering transformers or generators are made, but, in connection with each motor, a small pair of auto, or one-coil transformers, is used for starting. If speed regulation is also desired, as for cranes, the auto-transformers are made larger. From these auto-transformers several loops or connections are brought out. For regulating the speed these are connected to the contact plates or dials of a controller, as shown in Figs. 25 and 26. But for starting purposes only, when but one loop from each transformer is used, a pair of switches are used in connection with the transformers. With the switches open, the motor is disconnected. Throwing one direction starts the motor at reduced voltage and brings it up to almost full speed. The switches are then thrown over to full electro-motive force.

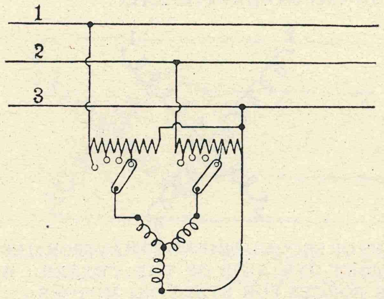


FIG. 26—DIAGRAMMATIC ARRANGEMENT OF AUTO-TRANSFORMERS AND CONTROLLER FOR REGULATING SPEED OF THREE-PHASE MOTOR BY VARYING THE VOLTAGE.

Two small transformers in a case with one four-jaw, throw-over switch, form what is called an "auto-starter." This is readily arranged for either two or three-phase circuits and motors. This makes a most flexible arrangement for starting, as the motor may be put at any location, and the auto-starter may be put in the most convenient position. It also loads all the line wires equally at start, and each motor and starter really form a unit separate from all the others. One pair of transformers may be connected to several sets of switches and thus be used for starting several motors.

Where motors are close to reducing transformers, the secondaries of the transformers may have loops brought out, to which one or more switches are connected. The primaries of the transformers may have loops connected to proper switches, and the number of primary turns in the circuit may be varied instead of the secondary. This is applicable when the transformers supply only one motor, or when several motors are started at the same time. A regulator with secondary movable with respect to the primary may be used. Regulators of this type vary the electro-motive forces without any "make" or "break" devices, and consequently have no sparking tendency. But they are in general too complicated and costly to compete with the transformer with loops.

Varying the Motor Connections

This is not a method for changing the electro-motive force applied, but for varying the number of turns in series with a given electro-motive force, and the effect is the same as varying the applied electro-motive force. This method is rather limited in its application owing to the complication involved. The simplest case for two-phase motors is a series-parallel combination of the windings of each phase. This is equivalent to using 0.5 electro-motive force at start. For three-phase motors, series-parallel may be used or the winding may be thrown from the star system of connection at start to the delta system for running. This is equivalent to using about 0.6 electro-motive force for start. But, as the star connection is preferred for the running condition, this combination is not advisable.

Choke Coils or Resistance in the Primary

There is a fourth method of regulation which may be mentioned, but which is not advisable in general practice. This is the use of choke coils or resistance in the primary circuits of the motor, to reduce the electro-motive force. These really give varying electro-motive forces. With choke coils, the power factor at start is lowered, with correspondingly bad effect on the generator and system. With ohmic resistance in the primary circuit, the reduction of electro-motive force is accompanied by a consumption of energy in the primary circuit which in no way represents torque.

THE TECHNICAL STORY OF THE FREQUENCIES

FOREWORD—This paper was presented before the Washington Section of the American Institute of Electrical Engineers in January, 1918. It covers briefly the history of the various frequencies used in America and the engineering and technical reasons which have influenced their ultimate choice or rejection. The author had in mind the preservation of this in more or less historical form, in order that it should not eventually be entirely lost. Since the publication of this paper, the author has received many favorable comments on it, as being the only reliable source of information on the subject which is now available. It has been reprinted in its entirety in a number of technical papers and the material drawn from it has been used in a number of technical lectures by various engineers and educators.—(Ed.)

THE STORY of how and why the various commercial frequencies came into use and then dropped out again, in most cases, is not primarily the story of the frequencies themselves, but of the various uses to which the alternating current has been applied.* In other words, fundamental changes in the application of alternating current have led to radical changes in the frequencies. Some of the applications which have had a determining factor on the frequency of the supply system are as follows; incandescent lighting, transformers, transmission systems, arc lighting, induction motors, synchronous converters, constructional conditions in rotating machinery, and operating conditions. A brief consideration of these items individually, from the present viewpoint, indicates that while some of them had, at one time, very considerable influence in determining frequency conditions, yet, in a number of cases, the original reasons have disappeared through improvements and refinements, as will be described later.

At various times the following standard frequencies have been in use in this country, namely, $133\frac{1}{3}$, 125, $83\frac{1}{3}$, 66 2/3, 60, 50, 40, 30 and 25 cycles per second. These did not appear chronologically in the order given above, and a few odd frequencies in a few special applications are omitted.

In the following, the various frequencies will be considered more or less in the order of their development and basic reasons will be given for their choice, and the writer will endeavor to show why certain of them have persisted, while others have dropped out. It will also be shown why the commercial situation has first tended strongly toward certain frequencies and afterwards swung toward others.

133 and 125 Cycles

In the earliest alternating work, the whole service consisted of incandescent lighting, and the electric equipment was made up of small high-speed belted single-phase generators and house-to-house distributing transformers. As the transformers were of small capacity and as their design was in a very crude state, it was believed that a relatively high frequency would best meet the transformer conditions. A choice of such an odd frequency as $133\frac{1}{3}$ cycles per second, is due to the fact that in those early days (1886 to 1893) frequencies were usually designated in terms of alternations per minute. One of the earliest commercial generating units constructed by the Westinghouse company had a speed of 2000 rev. per min. and had eight poles. This presented a fairly convenient constructional arrangement for the surface-wound type of rotating armature, which was the only one recognized at that time. The speed of 2000 rev. per min., with eight poles, gave 16,000 alternations per minute, or $133\frac{1}{3}$ cycles per second according to our present method of designation. Thus the earliest frequency in commercial use in this country was fixed, to a certain extent, by constructional reasons, although the house-to-house transformer problem apparently indicated the need for a relatively high frequency. The Thomson-Houston company adopted a standard frequency of 15,000 alternations per minute, (125 cycles) instead of the Westinghouse 16,000, but the writer does not know why this difference was made. However, the two frequencies were so close together that practically they could be classified as one.

At this time, it should be borne in mind, there were no real transmission problems, no alternating-current arc lighting, no induction motors and the need for uniform rotation of the generators was not recognized. The induction motor, in its earliest stages, came in 1888 and considerable work was done on it in 1889 and 1890, but it required polyphase supply circuits and comparatively low frequency and, therefore, it had no connection whatever with the then standard single-phase, $133\frac{1}{3}$ and 125 cycle systems. The synchronous converter was also unheard of (one might say almost undreamed of) at that time.

60 CYCLES

In 1889 or 1890 it was beginning to be recognized in this country that some lower frequency than 125 and $133\frac{1}{3}$ cycles would be desirable. Also about this time direct-coupled and engine-type alternators were being considered in Europe and it was felt that such construction would eventually come into use in America. It was appreciated that in such case, $133\frac{1}{3}$ cycles would present very considerable difficulties compared with some much lower frequency, due to the large number of poles which would be required. For instance, an alternator direct driven by an 80-rev. per min. engine would require 200 poles to give the required frequency and such construction was looked upon as being practically prohibitive. About this time Mr. L. B. Stillwell, then with the Westinghouse company, made a very careful study of this matter of a new frequency, in connection with the possibilities of engine type generators, and after analyzing a number of cases, it appeared that 7200 alternations per minute (60 cycles per second), was about as high as would be desirable for the various engine speeds then in sight. Transformer constructions and arc lighting were also considered in this analysis. While it was deemed that a somewhat higher frequency might be better for transformers, yet a lower frequency than 60 cycles was considered as possibly better for engine type generators. A compromise between all the various conditions eventually led to 60 cycles as the best frequency. However, while this frequency originated about 1890, it did not come into use suddenly, for it was impossible to introduce such a radical change in a brief time. Moreover, the direct-coupled or engine-type generator was slow in coming into general use and, therefore, there was not the necessity for the introduction of this low frequency in many of the equipments sold from 1890 to 1892. However, by 1893, 60 cycles became pretty firmly established and was sharing the business with the $133\frac{1}{3}$-cycle systems. It should be borne in mind that, at this time, the adoption of this frequency was not considered as a direct means for bringing forward the polyphase induction motor, for the earlier 60-cycle systems, like the 125- and $133\frac{1}{3}$-cycle, were all single-phase Also, it was then thought that the polyphase motor would possibly require a still lower frequency and, moreover, the polyphase system was looked upon as in a class by itself, suitable only for induction motor work. At that time the introduction of polyphase generators for general service was not contemplated. This followed about two or three years later.

In 1890 the Westinghouse company, which had been developing the Tesla polyphase motor. laid aside the work, largely on account of there being no suitable general supply systems for this type of motor. The problem was again revived in 1892, in an experimental way, with a view to bringing out induction motor which might be applied on standard frequencies such as could be used in commercial supply circuits for lighting and other purposes. It should be understood that at this time such circuits were not in existence but were being contemplated. In 1893, after the polyphase motor had been further developed up to the point where it showed great commercial possibilities, the best means for getting it on the market were carefully considered. It was decided that the best way to promote the induction motor business was to create a demand for it on commercial alternating-current systems. This meant that, in the first place, such systems must be created. Therefore, it was decided to undertake to fill the country with polyphase generating systems, which were primarily to be used for the usual lighting service. It was thought that, with such systems available, the time would soon come when there would be a call for induction motors. In this way experience would be obtained in the construction and operation of polyphase generators and the operating public would not be unduly handicapped in the use of such generators, compared with the older single-phase types.

An early example of this new practise was in the 2000-kw. polyphase generating units used for lighting the Chicago World's Fair in 1893. Here the single-phase type still persisted, as each generator unit was made up of two similar frames placed side by side, but with their single phase armatures displaced one-half pole pitch from each other so that the combined machine delivered two single-phase currents displaced 90 degrees from each other. It was considered that each circuit could be regulated independently for lighting service, and polyphase motors could be operated from the two circuits. These generators (at that time the largest in this country) were designed in 1892 and were of 60 cycles. These, therefore, indicate the tendency at that time toward lower frequency and polyphase generation, although commercial polyphase motors were not yet on the market.

25 CYCLES

At the same time that 60 cycles was selected as a new standard it was recognized that at some future time there would be a place for some much lower frequency, but it was not until two years later that this began to narrow down to any particular frequency. In 1892 the first Niagara electrification, after several years consideration by eminent authorities, had centered on polyphase alternating current as the most desirable system. The engineers of the promoting company had also worked out what they considered the most suitable construction of machine. This involved 5000-h. p. units at 250 revolutions per minute. Prof. George Forbes, one of the engineers of the company had furnished the electrical designs for a machine with an external rotating field and an internal stationary armature. His design used eight poles, thus giving 2000 alterations per minute, or $16\frac{2}{3}$ cycles per second. Quite independently of this, the Westinghouse company, in 1892, had been working on the development of synchronous converters, using belted 550-volt d-c. generators with two-phase collector rings added. The tests on these machines had shown the practicability of such conversion and had even proved at this early date, that the converter copper losses were much lower than in the corresponding d-c. generators. Thus it is an interesting fact that the first evidence of this important principle was obtained from a shop test rather than by calculation. The writer, from an analysis of the tests, which were made under his immediate direction, concluded that the armature copper losses must be considerably lower than in the same machine used as a d-c. generator. He also brought the matter to the attention of Mr. R. D. Mershon, then with the Westinghouse company, and the problem was then worked out mathematically by him and the writer, in two quite different ways, but with similar results, showing that the converter did have actually very much reduced copper losses.

As a result of this work of the Westinghouse company on the synchronous converter, it was decided that, to make such machines practicable, some suitable relatively low frequency was required. This appeared to be about 30 cycles. About this time the construction of the Niagara generators was taken up with the Westinghouse company to see whether it would construct these machines according to the designs submitted by the promoting company's engineers. These designs were gone over as carefully as the knowledge of such apparatus, at that time, permitted, and many apparent defects and difficulties were pointed out. The Westinghouse company then proposed, as a substitute, a 16-pole, 250-rev. per min. machine (the speed being definitely fixed at 250 rev. per min.). This gave $33\frac{1}{3}$ cycles or as near to the Westinghouse proposed 30 cycle system, as it was possible to get. Then many arguments were brought forward, pro and con, for the two machines and frequencies. Prof. Forbes' preference for $16\frac{2}{3}$ cycles was based partly on the possibilities it presented for the construction and operation of commutator type motors, just as with direct current circuits. The Westinghouse contention was that this frequency was too low for any kind of service except possibly commutator type machines. Tests were made with incandescent lights and it was found that at $33\frac{1}{3}$ cycles there was little or no winking of light, while at $16\frac{2}{3}$ cycles, the winking was extremely bad. Tables were also made up, showing the limited number of speed combinations at $16\frac{2}{3}$ cycles for induction motors, in case such should come into use. This showed how superior the $33\frac{1}{3}$ cycles would be as regards such apparatus. It was also brought out that synchronous converters, when such became commercial, would be much better adapted for the higher frequency, as the choice of speeds would be much greater. From the present viewpoint the arguments appear to have been much in favor of the Westinghouse side of the case.

As a consequence of all this discussion the suggestion was advanced by some one, that a 12 pole, 250-revolution machine, (that is, 3000 alternations, or 25 cycles), might meet sufficiently the good qualities of both of the proposed frequencies and would thus be a good compromise. In consequence a 12-pole, 25-cycle machine was worked up by the Westinghouse company and eventually this frequency was adopted for the Niagara generators. Afterwards, while these generators were being constructed it was brought out pretty strongly that the great advantage of this frequency would be in connection with synchronous converter operation, but that it was also extremely well adapted for slow-speed engine type generators, which were then coming into use. In consequence of the prominence given this frequency it was soon adopted as a standard low frequency, especially in those plants where synchronous converters were expected to form a prominent part of the system.

However, while 60 and 25 cycles came into use, as described above, it must be recognized that they had competitors. For instance, 66⅔ cycles (8000 alternations or one-half of 16,000) was used to a considerable extent by one of the manufacturing companies. Also 50 cycles came into use in certain plants and, to a certain extent, is still retained, but has become the standard high frequency of Europe. Instead of 25 cycles, the Westinghouse company advocated 30 cycles for some of its plants, largely because with the 25 per cent higher speeds permissible with such frequencies, the capacities of induction motors could be correspondingly increased and also incandescent lighting was more satisfactory. However, it was soon recognized that the 66⅔ and 30 cycle variations from the two leading frequencies of 60 and 25 cycles were hardly worth while, and they were gradually dropped, except in plants already installed. A brief attempt was made at a somewhat later period to place 40 cycles upon the market as a substitute for both 25 and 60 cycles. This was done under the impression that 40 cycles would give a universal system for arc and incandescent lighting, transmission, induction motors, synchronous converters and about everything else. This frequency possessed many merits and it was thought, at one time, that it might win out, but apparently the other two frequencies were too well established, and the 40 cycle system eventually lost ground.

The problem of the frequencies finally narrowed down to the two standards, and these two were accepted because it was thought that they covered such entirely different fields of service that neither of them could ever expect to cover the whole. In other words, two standards were required to cover the whole range of service. It was recognized that 25 cycles would not take care of alternating-current arc lighting and that it was questionable for incandescent lighting in general. In other ways, such as suitability for engine-type construction, application to induction motors and synchronous converters and transmission of power to long distances, it met the needs of an ideal system, as then understood. Also, in parallel operation of engine-type alternators, which was one of the serious problems of those days, the 25-cycle machines were unquestionably superior to the 60-cycle ones, due to the lesser displacement of the e. m. f. waves with respect to each other with a given angular variation in the engine speeds. However, although the 25-cycle system presented so many advantages, it could not take care of the lighting business, and, therefore, could not entirely dominate the situation.

As regards 60 cycles, it was felt that this could handle the direct lighting situation in a very satisfactory manner and was possibly better suited for transformers than 25 cycles, although there were differences of opinion in this matter, especially when it came to the larger capacities. It was reasonably well adapted for induction motors in general, but not for very low speeds. In matters of transmission and in the operation of synchronous converters it was thought to be vitally defective.

From the above consideration it would appear that the 25-cycle systems presented the stronger showing as a whole and, therefore, there was a decided tendency toward this frequency, except in those cases where lighting directly from the alternating-current system was considered of prime importance. In those systems, such as many of the Edison companies, where low-voltage three-wire direct current was used from synchronous converters, the tendency was almost solidly toward the 25-cycle system. In those days the central station, which had gotten itself committed to the 60-cycle system so deeply that it could not change, was looked upon with commiseration. Sixty-cycle plants were looked upon, to a certain extent, as a necessary evil. In fact, so strong was the tendency toward 25 cycles that in many cases 25-cycle plants were installed for industrial purposes, where 60 cycles would have been better. The 25-cycle synchronous converter development advanced by leaps and bounds and the machines were so good in their operation that it was believed that 60-cycle converters could never be really competitive with them.

On the other hand, in those large plants, which were so "unfortunate" as to have 60 cycles installed, many apparent makeshifts were adopted to meet the various service requirements.

In arc lighting, incandescent lighting, transformers and motors there was no need for makeshifts. However, in conversion to direct current, one of the greatest difficulties appeared. There were many who advocated motor-generators for this purpose, largely because the 60-cycle converter was thought to be impracticable, in spite of the fact that the manufacturing companies were putting them on the market. The 60-cycle converter at that time bore a bad name. It is now recognized that many of the faults of the early 60-cycle synchronous converter operation were not in the converters themselves, but were, to a considerable extent, in the associated apparatus. Low-speed engine-type, 60-cycle generators were not always adapted for operation of synchronous converters. In fact, in numerous cases such generators would not operate in an entirely satisfactory manner in parallel with each other, and yet when it was attempted to operate synchronous converters from these same generators the unsatisfactory results were not blamed upon the generating system but upon defects of the converters themselves. Unfortunately, defects in the generating and transmission systems usually appeared in the converters as sparking and flashing, and such troubles naturally would be credited to defects in the construction of the converters themselves. In fact, in those days, 60-cycle converters were expected to do things which now are considered as absurd. For instance, in one case in the writer's knowledge a 60-cycle synchronous converter was criticized as being a very badly designed piece of apparatus, due to serious flashing at times. Investigation developed that this converter was expected to operate on either one of two independent 60-cycle systems with no rigid frequency relation to each other. The converter in service was thrown from one system to the other indiscriminately, and sometimes it flashed in the transfer and sometimes it did not. The machine was considered to be "no good" because it would not always stand such switching.

At one time the writer stood almost alone in his belief that the 60-cycle synchronous converter presented commercial possibilities sufficient to make it a strong future contender with the 25-cycle machine, provided proper supply conditions were furnished and certain difficulties in the proportions of the converter itself were overcome. One basis for his contention was that in some of the 60-cycle plants, where the generator rotation was quite uniform, the converters were evidently much superior in their operation to other plants, using slow-speed engine-type generators with considerable periodic variations. In such plants the hunting tendency of the converters was very greatly reduced, with consequent improvement in sparking and general operation. It was early recognized that hunting was a very harmful condition, both in 60- and 25-cycle synchronous converters, but whereas it was a relatively rare condition in 25-cycle plants it was much more common with 60 cycles. However, the operating public was not particularly concerned whether the trouble was in the generating plant or in the converters themselves, as long as such trouble existed and was not overcome. Very early in the synchronous converter development it was found that hunting would produce sparking or flashing at the commutators of the converters. However, even in those plants where there was no hunting apparent, there was difficulty at times due to flashing, especially with sudden change of load, which resulted in temporary increase in the d-c. voltage. This was a difficulty which was inherent in the converter itself and could not be blamed entirely upon the generating or transmitting conditions, for 25-cycle machines were practically free from this trouble under similar conditions of operation. Investigation developed the fact that this flashing trouble was due largely to unduly high value of the maximum volts between commutator bars. This difficulty was recognized long before it was overcome, simply because certain physical limitations in construction had to be removed. There were two ways in which the maximum volts per bar could be reduced, namely, by increasing the number of commutator bars per pole and by decreasing the ratio of the maximum volts to the average volts per bar, that is, by increasing the ratio of the pole width to the pole pitch, but both of these involved structural limitations in the allowable peripheral speeds of the commutator and the armature core. Here is where a little elementary mathematics comes in. The peripheral speed of the commutator is directly proportional to the distance between adjacent neutral points on the commutator, and the frequency. Therefore, with a given frequency the distance between the adjacent neutral points is directly proportional to the peripheral speed. Thus, a commutator speed of 4500 ft. per min. which was then considered an upper limit, the distance between adjacent neutral points on a 60-cycle converter is only $7\frac{1}{2}$ in. (19 cm.) This distance is thus fixed mathematically and is independent of the number of poles or revolutions per minute, or anything else, except the peripheral speed and the frequency. With this distance of 7½ in., (19 cm.), about the only choice in commutator bars per pole was 36, giving an average of 16⅔ volts per bar on a 600-volt machine, and nearly 20 volts per bar with momentary increase of voltage to 700, which is not uncommon in railway service.

However, it is not this average voltage which fixes the flashing conditions, but it is the maximum voltage between bars, and this is dependent upon the average voltage and upon the ratio of the pole width to the pole pitch. Here is where one of the serious difficulties came in. As mentioned above the pole pitch is directly dependent upon the peripheral speed of the armature core and the frequency. Therefore, in a 60-cycle machine, if the peripheral speed is fixed, the pole pitch is at once fixed. For example, with an armature peripheral speed of 7200 ft. per min., which was considered high at that time, the pole pitch becomes 12 in. (30.48 cm.), regardless of any other considerations, and here was where a most serious difficulty was encountered. If a sufficiently wide neutral zone for commutation was allowed the interpolar space became so wide that there was not enough left for a good pole width. For instance, if the interpolar space was made 6 in. (15.24 cm.) wide, in order to give a sufficiently wide commutating zone to prevent sparking or flashing, due to fringing of the main field, then this left only 6 in. for the pole face. With this relatively narrow pole face the ratio of the maximum volts to the average volts was so high that with the 36 commutator bars per pole the machine was sensitive to arcing between commutator bars thus resulting in flashing. By widening the pole face this difficulty would be lessened or overcome but with the fixed pole pitch of 12 in. (30.48 cm.) the neutral zone would be so narrowed as to make the machine sensitive to sparking and flashing at the brushes. Thus, no matter which way we turned we encountered trouble. Obviously there were two directions of improvement, namely, by increasing the number of commutator bars, thus reducing the average voltage, and by increasing the pole pitch, thus allowing relatively wider poles with a given interpolar space. These two conditions look simple and easy, but it took several years of experience to attain them. When we have reached apparent physical limitations in a given construction, especially when such limitations are based upon long experience, we have to feel our way quite slowly toward higher limitations. For instance, in the case of the 60-cycle converters we could not boldly jump our peripheral speeds 20 to 25 per cent higher and simply assume that everything was all right. We first had to build apparatus and try it out for a year or so. Troubles, due to peripheral speed, do not always become apparent at once, and thus time tests are necessary Therefore, while the peripheral speeds of the 60-cycle synchronous converters were actually increased 20 to 25 per cent practically in one jump, yet it took two or three years of experimentation and endurance tests before the manufacturers felt sure enough to adopt the higher speeds on a broad commercial scale. Thus, while the change from the older more sensitive type of 60-cycle converter to the later type occurred commercially within a comparatively short period yet the actual development covered a much longer period.

Let us see now what an increase of 25 per cent in the peripheral speeds actually meant. As regards the commutator, the number of bars could be increased 25 per cent, that is, from 36 to 45 per pole, which was comparable with ordinary d-c. generator practise. In the second place, an increase of 25 per cent in the peripheral speed of the armature core meant a 15-in. (38.1-cm.) pole pitch, where 12 in. (30.8 cm.) was used before. Assuming, as before, a 6-in. (15.24-cm.) interpolar space, then the pole face itself became 9 in. (22.8 cm.) in width instead of 6 in. (15.24 cm.) or an improvement of 50 per cent. In fact, this latter improvement was so great that some manufacturers did not consider it necessary to increase the number of commutator bars, although in the Westinghouse machines both steps were made.

The above improvements so modified the 60-cycle converter that it began to approach the 25-cycle machine in its general characteristics. It was still quite expensive compared with the 25-cycle, due to the large number of poles, and its efficiency was considerably lower than its 25-cycle competitor, on account of high iron and windage losses. However, due to the need for such a machine it was gradually making headway, in spite of handicaps in cost and efficiency.

Almost coincident with the initiation of the above improvements in the 60-cycle converter, came another factor which has had much to do with the success of this type of machine. This was the advent of the turbo-generator for general service. As stated before, one of the handicaps of the 60-cycle converter was in the non-uniform rotation of the engine type generators which were common in the period from 1897 to about 1903 or 1904. But, about this latter date, the turbo-generator was making considerable inroads on the engine-type field and within a relatively short period it so superseded the former type of unit, that it was recognized as the coming standard for large alternating power service. With the turbo-generator came uniform rotation and this at once removed one of the operating difficulties of the 60-cycle converters. However, in the early days of the turbo-generator, 25 cycles still was in the lead and many of the earlier generators were made for this frequency, especially in the larger units. But it was not long before it was recognized that 60 cycles presented considerable advantage in turbo-generator design due to the higher permissible speeds. In the earlier days of turbo-generator work, this was not recognized to any extent, as the speeds of all units were so low that the effect of any speed limitations was not yet encountered. For instance, a 1500-kw, 60-cycle turbo-generator would be made with six poles for 1200 revolutions, while a corresponding 25 cycle unit would be made with two poles for 1500 revolutions. This slightly higher speed at 25 cycles about counterbalanced the difficulties of the two-pole construction compared with the six-pole. However, before long, more experience enabled the six pole, 60-cycle machine to be replaced at 1800 revolutions, and a little later by two poles at 3600 revolutions. This, of course, turned the scales very much in the other direction. In larger units, however, the advantage still appeared to be in favor of 25 cycles, but in the course of development, 1500 revolutions was adopted quite generally for 25-cycle work, and this was the limiting speed, as such machines had only two poles, or the smallest number possible with ordinary constructions. On the other hand, for 60 cycles, 1800 revolutions was adopted quite generally for units up to almost the extreme capacities that had been considered, consequently the constructional conditions in the large machines swung in favor of 60 cycles. Therefore, with the coming of the steam turbine and the development of high-speed turbo-generator units, the tendency has been strongly toward 60 cycles. This, with the greater perfection of the 60-cycle converter, had much to do with directing the practise away from the 25 cycles.

However, there were other conditions which tended strongly toward 60 cycles. In the early development of the induction motor, the 25-cycle machines were considerably better than the 60-cycle and possibly little or no more expensive. However, as refinements in design and practise came in, certain important advantages of the 60-cycle began to crop out. For instance, with 25 cycles there is but little choice in speed, for small and moderate size motors. At this frequency a four-pole motor has a synchronous speed of only 750. The only higher speed permissible is 1500 revolutions with two poles, and it so happens that in induction motors the two-pole construction is not materially cheaper than the four pole, consequently the principal advantage in going to 1500 revolutions was only in getting a higher speed where such was necessary for other reasons than first cost. However, in 60 cycles the case is quite different, where a four-pole machine can have a speed of 1800 revolutions, synchronous, a six pole 1200, an eight pole 900 and a ten pole 720 revolutions. In other words, there are four suitable speed combinations where a 25 cycle motor had only one. Moreover, with the advance in design it developed that these higher speed 60-cycle motors could be made with nearly as good performances as with the 25-cycle motors of same capacity, and at somewhat less cost. However, leaving out the question of cost, the wider choice of speeds alone would be enough to give the 60-cycle motor a pronounced preference for general service.

However, there is one exception to the above. Where very low-speed motors are required, such as 100 rev. per min., the 60-cycle induction motor is at a considerable disadvantage compared with 25 cycles, or this has been the case in the past. It is partly for this reason that the steel mill industry, through its electrical engineers, adopted 25 cycles as standard some ten or fifteen years ago. At that time, it was considered that in mill work, in general, there would be need for very low-speed motors in very many cases. However, due to first cost, as well as other things, there has been a tendency toward much higher speeds in steel mill work, through the use of gears and otherwise, so that part of this argument has been lost. However, there still remain certain classes of work where direct connected very low-speed induction motors are desirable and where 25 cycles would appear to have a distinct advantage.

In view of the above considerations, steel mill work has heretofore gone very largely toward 25 cycles, particularly where the mills installed their own power plants. However, in recent years there has been a pronounced tendency toward purchase of power, by steel mills, from central stations, and the previously described tendency of central stations toward 60 cycles has forced the situation somewhat in the steel mills, particularly in those cases where the central power supply company can furnish power at more reasonable rates than the steel mill can produce in its own plant. This, therefore, has meant a tendency toward 60 cycles in steel mill work, even with the handicap of inferior low-speed induction motors. But, on the other hand, remedies have been brought forward even for this condition. The great difficulty in the construction of low-speed, 60-cycle induction motors is in the very large size and cost if constructed for normal power factors, or the very low power factor and poor performance if constructed of dimensions and costs comparable with 25 cycles. In the latter case the extra cost is not entirely eliminated because a low power factor of the primary input implies additional generating capacity, or some means for correcting power factor on the primary system. However, in some cases it is entirely practicable to correct the power factor in the motors themselves by the use of so called "phase advancers" of either the Leblanc or the Kapp type. Such phase advancers are machines connected in the secondary circuits of induction motors and so arranged as to furnish the necessary magnetizing current to the rotor or secondary instead of to the primary In this way the primary current to the motor will represent largely energy and the power factors can be made equal to, or even much better than in, the corresponding 25-cycle motor; or, in some cases, the conditions may be carried even further so that the motor is purposely designed with a relatively poor power factor, in order to further reduce the size and cost, and the phase advancers are made correspondingly larger. In those cases where the cost of the phase advancer is relatively small compared with the main motor, there may be a considerable saving in the cost of the main motor and then adding part of the saving to the cost of the phase advancer.

One difficulty in the use of phase advancers is found in the variable speeds required in some kinds of mill work. In those cases where flywheels driven by the main motors are desirable to take up violent fluctuations in load, it is necessary to have considerable variations in the speed of the induction motor, in order to bring the stored energy of the flywheel into play. Unfortunately this variable speed in the induction motor is one of the most difficult conditions to take care of with a phase advancer, so that here is a condition where the 60-cycle motor is at a decided disadvantage.

Thus it may be seen from the above that even in the steel mill field, where the induction motor has the most extreme applications, there is quite a strong tendency toward 60 cycles, due to the purchase of power from central supply systems.

There remains one more important element which has had something to do with the tendency toward 60 cycles, namely, the transmission problem. In the earlier days of transmission of alternating current, 25 cycles was considered very superior to 60 cycles due to the better inherent voltage regulation conditions. At one time, it was thought that 60 cycles had a very limited field for transmission work. However, a number of power companies in the far west had installed 60-cycle plants, principally for local service and with the growth of these plants came the necessity for increased distance of transmission through development of water powers. At first it was thought they were badly handicapped by the frequency, but gradually the apparent disadvantages of their systems were overcome and the distances of transmission were extended until it became apparent that they could accomplish practically the same results as with 25 cycles. Part of this result has been obtained by the use of regulating synchronous condensers. It is a curious fact that the possibility of synchronous motors used as condensers for correction of disturbances on transmission systems, has been known for about 25 years, but it is only within quite recent years that they have come into general use as a solution of the transmission problem, and largely in connection with 60-cycle plants. In 1893 the writer applied for a patent on the use of synchronous motors as condensers for controlling the voltage at any point on a transmission system by means of leading or lagging currents in the condenser itself. A broad patent was obtained, but there was no particular use made of it until it had practically expired.

Another improvement came along which still further helped to advance 60 cycles to its present position, namely, the use of commutating poles in synchronous converters. The principal value of commutating poles in the 60-cycle converters, has not been so much in an improvement in commutation over the older types of machines, as in allowing a very considerable reduction in the number of poles with corresponding increase in speed, resulting in reduction in dimensions. As a direct result of this increase in speed the efficiencies of the converters have been increased. If, for instance, the speed of a given 60-cycle converter can be doubled by cutting its number of poles to one-half, while keeping the same pole pitch and the same limiting peripheral speed, then obviously the amount of iron in the armature core is practically halved and, at the same magnetic densities the iron loss is also practically halved. Also with the same peripheral speed and half diameter of armature the windage losses can be decreased materially. Thus the two principal losses in the older converters have been very much reduced. There have also been reductions in the total watts for field excitation, and in other parts, so that, as a whole, the efficiency for a given capacity 60-cycle converter has been brought up quite close to that of the corresponding 25-cycle machine, even when the latter is equipped with commutating poles. This gain of the higher frequency compared with the lower is due to the fact that the lower-frequency machine was much more handicapped in its possibilities of speed increase, and furthermore, the iron losses and windage represented a much smaller proportion of the total losses in the low-frequency machine. This improvement in the efficiency of the 60-cycle converter together with the lower losses in the 60-cycle transformer as compared with the 25-cycle, has brought the 60-cycle equipment almost up to the 25-cycle, so that the difference at present is not of controlling importance. This development has given further impetus toward the acceptance of 60 cycles as a general system.

Formerly a serious competitor with the 60 cycle converter was the 60-cycle motor-generator. This was installed in many cases because it was considered more reliable and more flexible in operation than the synchronous converter. Both of these claims were true to a certain extent. However, with improvements in the synchronous coverter the difference in reliability practically disappeared, but there remained the difference in flexibility. In the motor-generator set, the d-c. voltage could be varied over quite a wide range, while in the older 60-cycle rotaries the d-c. voltage held a rigid relation to the alternating supply voltage. However, with the development and perfection of the synchronous booster type of converter, flexibility in voltage was obtained with relatively small increase in cost and minor loss in economy. This has been the last big step in putting the 60-cycle converter at the front as a conversion apparatus, so that today it stands as the cheapest and most economical method of converting alternating current to direct current. Moreover, while the 25-cycle synchronous converter has apparently reached about its upper limit in speed, there are still possibilities left for the 60-cycle converter.

In line with the above it is of interest to note that for units of 1000 kw. and less, the 60-cycle converter has nearly driven the 25-cycle out of business from the manufacturing standpoint.

For the very large size converters, 25 cycles still has the call, but largely in connection with many of the railway and three-wire systems, which have been installed for many years; that is, the growth of this business is in connection with existing generating systems. However, the 60-cycle converter, in large capacity units, is gaining ground rapidly and it is of interest to note that the largest converters yet built, namely, 5800 kw., are of the 60-cycle type.

One most interesting point may be brought out in connection with the above described "battle of the frequencies", namely, it was fought out in the operating field, and between conditions of service, and not between the manufacturing companies. This is a very good example of how such matters should be handled. Here the engineers of the manufacturing companies were expending their efforts to get all possible out of both frequencies, and consequently development proceeded apace. When 60-cycle frequency seemed to be overshadowed by its 25-cycle competitor, the engineers took a lesson from the latter and proceeded to overcome the shortcomings of the former. It was no innate preference of the designing engineers that has brought the higher frequency to the fore; it was the recognition that it had greater merits as a general system, if its weak points could be sufficiently strengthened; and, therefore, the engineers turned their best efforts toward accomplishing this result.

It must not be assumed, for a moment even, that because 60 cycles appears to be the future frequency in this country, that 25 cycles was a mistake. Decidedly it was not. In reality it formed a most important step toward the present high development of the electric industry. Many things we are now accomplishing with 60 cycles would possibly never have been brought to present perfection, if the success of the corresponding 25-cycle apparatus had not pointed the way. The success of the 25-cycle converter, and the high standard of operation attained, gave ground for belief that practically equal results were obtainable with 60 cycles. Therefore, the 25-cycle frequency served a vast purpose in electrical development; it was a high class pacemaker, and it isn't entirely out-distanced yet.

There has been considerable speculation as to what two standard frequencies would have met the needs of the service in the best manner, and would have resulted in the greatest development in the end. It has been claimed by some, that 50 and 25 cycles would have been better than 60 and 25. In the earlier days possibly the former would have been better, but as a result both standards might have persisted longer. In any case, the general advantages would have been small. In one class of machines, namely, frequency changers, consisting of two alternators coupled together, the 25-50 combination would certainly have been advantageous.

Again it has been questioned whether 30 and 60 cycles would not have been a better choice. This was the original Westinghouse choice of frequencies, but not on account of frequency changers. As stated before, it was felt that 30 cycles could do about all that 25 cycles could, and would give an advantage of 25 per cent higher speed in motors and converters, with correspondingly higher capacities. Also for direct coupled alternators, the two-to-one ratio of frequencies would fit in nicely with engine speeds, in most cases. Possibly, from the present viewpoint, the choice of thirty cycles, would have longer retained the double standard.

Something further may be said regarding the 40-cycle system, brought out by the General Electric Company. This contained many very good features, for the time it was brought out. It was then believed that if the 60 cycle frequency was retained, the double standard was necessary. The 40-cycle system was an attempt to eliminate this double standard. It apparently furnished a better solution than 60 cycles then promised for the synchronous converter problem, and was a fair compromise in about everything else. But it came too late, for the 25-cycle system was too firmly entrenched, and for further development, the designing engineers preferred to expend their energies in seeing what could be accomplished with 60 cycles, as this seemed to present greater possibilities than either 25 or 40, if it could be sufficiently perfected. Thus the 40-cycle system probably missed success due to being just a little too late.

As to 50 cycles, it was stated that this is still in use to a limited extent. Most of the 50-cycle plants in this country are in California. Such plants were started during the nebulous period of the frequencies, and have persisted, to a certain extent, partly because certain 60-cycle apparatus could be easily modified to meet the 50-cycle requirements. Also, as 50 cycles is the standard in many foreign countries to which this country exports equipment, the use of 50 cycles in some home plants has not been unduly burdensome from the manufacturers' standpoint.

In addition to the preceding, there have been certain classes

of electric service which have depended upon frequency, but which have not been a determining factor in fixing any particular frequency. Among these may be considered commutating types of a-c. apparatus. The first a-c. commutating motors of any importance, which appeared, were, of course, the 25-cycle, single-phase railway motors. These as a rule have operated from their own generating plants, or from other plants through frequency-converting machinery. One exception in the railway work may be noted in the use of 15 cycles on the Visalia plant in California. There is a pretty well defined opinion among certain engineers experienced in such apparatus that some low frequency, such as 15 cycles, would present very considerable advantages in the use of single-phase railway motors in very heavy service, such as on some of the western mountain roads. Here the problem is to get the largest possible motor capacity on a given locomotive, and the main advantage of the lower frequency would be in allowing a very materially higher capacity within a given space. This does not imply reduced weight or cost compared with the 25 cycles, but simply means greater motor capacity. With the modern, more highly developed, single-phase types of railway motors, it would appear that there may be very considerable possibilities in 15 cycles.

Outside of the railway field, there has been more recently a development of various types of a-c. commutating apparatus, principally in connection with heavy steel mill electrification work. Such apparatus has been largely in the form of three phase commutating machines and these have been used principally in connection with speed control of large induction motors. As these regulating machines are usually connected in the secondary circuits of induction motors, the frequency supplied is represented by the slip frequency. Consequently where the slip frequency never rises to a large percentage of that of the primary system, such commutating motors are applicable without undue difficulties. Such motors, presumably are better adapted for 25-cycle mill equipments than for 60-cycle, but due to the tendency, already described, for steel mills to go to 60 cycles on purchased power, it has been necessary to build these three-phase commutating motors for the regulation of 60-cycle main motors, in many cases.

There is still another class of service, which has come in recently, where the choice of frequency is of much importance, but where there is no great necessity for adhering to any standard.

namely, in heavy ship propulsion by electric motors. As each ship equipment is a complete system in itself, and as it cannot tie up with other systems, there is not any controlling need for maintaining any definite frequency or voltage. Except in similar vessels, there is little chance for duplication in parts, as the various equipments vary so much in size and capacity. In consequence it has been found advisable, at least up to the present time, to design each propulsion equipment for that frequency which best suits the generator and motor speeds, taking into account the various operating conditions and limitations, such as the different running speeds, steaming radius, etc. In consequence, different maufacturers bidding on such equipments may specify different frequencies, depending upon the constructional features of their particular types of apparatus. At the present time with the relatively small amount of experience obtained with the electrical propulsion of ships, it looks as if it would be a considerable handicap to attempt to adopt some standard frequency for all service. Later, with wide experience, it may be possible to adopt some compromise frequency, which will not unduly handicap any of the service.

Conclusion

It has been the writer's intention to show that, as a rule, the choice of frequency has been a matter of most serious consideration, based upon service conditions at the time. Moreover, in view of the wide range of conditions encountered, it is surprising how few frequencies have been seriously considered in this country. Occasion has arisen, times without number, where an obvious solution of a given problem would lie in modification of the frequency to allow the use of apparatus and equipment already designed, but the engineers of the manufacturing organization have steadily held out against such policy, regardless of the apparent need of the moment. The swing of the pendulum from 60 cycles to 25 cycles and back, has covered a period of many years and, therefore, cannot be considered as a fad of the moment, but is the result of well defined tendencies, backed by the best engineering experience available. As a rule no manufacturer has made any particular frequency his "pet," but all have worked to develop each system to its utmost.

THE DEVELOPMENT OF THE ALTERNATING-CURRENT GENERATOR IN AMERICA

FOREWORD—The following article, which just appeared in the Electric Journal, contains a fairly complete brief history of the evolution of the alternating-current generator in so far as the Company with which the writer is connected is concerned, as drawn from the writer's memory principally. Reference is made incidentally to the work of other manufacturing companies, but this cannot be very complete, as the writer naturally does not have the necessary material available for describing such developments, except in a very general way. Therefore, the inadequacy of this history, out side of the Westinghouse part, should be charged to the lack of data rather than to lack of respect for the work of others.—(Ed.)

In the early days of the alternating-current generator, it was constructed in almost as many types as there were designers. The principal endeavor of each designer appeared to be toward the development of a new alternator which would bear his name. A few of these early types were of the rotating field construction, while a much greater number were of the rotating armature type. Some had iron core armatures, while others had coreless armatures, and there were many discussions as to whether the core or the coreless type was superior and would survive. Many of the early predictions would now form quite interesting reading, in view of the fact that present practice is so far removed from the early anticipations. Here and there among the early machines was one which contained some of the important elements of recent apparatus, but in many cases such machines disappeared in the general course of development, the meritorious features being insufficient to save the type.

Surface Wound Armatures

In America, the principal early type of alternator had a rotating armature with surface windings and an external cast iron multipolar field. This type was used very considerably or, in fact, almost exclusively, from 1886 to 1890. This was the type built by the Westinghouse and the Thomson-Houston Companies. There were only minor differences in the construction of the machines built by these two companies which, however, at that time, appeared to be very great. These differences consisted principally in the way the end windings of the armature coils were supported, in the construction of the end bells and ventilating openings in the armature core, in the method of attaching the armature core to the shaft, in the winding of the field coils in metal bobbins, etc. Both machines had surface windings with concentric coils, one layer deep in the radial direction. In the Westinghouse construction, the end windings were turned down toward the shaft and were supported by radial wooden clamps, as indicated in Fig. 1. In the Thomson-Houston armature, the end windings were arranged in an axial instead of a radial direction, and were supported by bands or external clamps. This construction is also indicated in Fig. 1. The Slattery machine, which was also on the market at that time, was of the same general type as the above machines. Presumably these two different methods of end winding were used on account of the patent situation. At that time there was much discussion of the respective merits of the two constructions.

These early machines were built principally for frequencies of 15,000 and 16,000 alternations per minute (125 and 133 cycles per second). In those days, everything was rated in alternations per minute, as this represented the product of the number of poles by the number of revolutions. Such high frequencies were selected, mainly, on account of transformer conditions, and not alternator design. Practically all alternating service consisted of house to house lighting, and in relatively small units, and the higher frequency was supposed to be of great advantage in transformer design and operation, which presumably was the case with the very small amount of data and experience available at that time.

About the only commercial voltage for alternating work at that time was 1000 or 1100 volts. This was supposed to be excessively high and dangerous, and there was much question whether such an excessive voltage should be permitted. This matter was actually taken before a number of the state legislatures for the purpose of obtaining laws prohibiting or limiting the use of such voltage. Another reason why no higher voltage was used was in the construction of the alternators and transformers. With the experience and materials available at that time, together with the high speed rotating armature construction and the surface windings, even 1100 volts was a very serious problem in the generator. About 1889 or 1890, there appeared some slight demand for higher voltages, and a few 2000 or 2200 volt surface-wound alternators, of the then standard type, were built. However, even then it was recognized that the surface-wound type of alternator was not well adapted for higher voltages, and there was much question whether a different type winding should not be developed for 1100 volts. This gradually led to the next big step, namely, the development of the "toothed" type of alternator with one big tooth per pole, in distinction from the slotted type of armature with a number of slots per pole, which was a considerably later development.

TOOTHED ARMATURES

The first commercial toothed type of armature appears to have been gotten out by the Westinghouse Company. These first machines were radically different, in details of construction, from the later toothed armature types of machines which came into general use. The first toothed armatures were small air-gap machines. In the surface-wound armatures, the clearance between the armature surface and the field poles was comparatively small, although the total air-gap (iron to iron) was large on account of the surface winding. In constructing the new toothed armature, the actual clearance (iron to iron) between armature and field was kept about the same as in the surface-wound alternators (bands to iron), but this clearance actually represented the total air-gap in the toothed type. Moreover, in sinking the windings below the surface, it was endeavored to maintain a practically uniform outside surface, so that overhanging tooth tips were used with relatively narrow slots for putting in the windings. The general construction was similar to Fig. 2. On account of the small clearance, and consequent higher magnetic conditions, it was found necessary to use lamin-

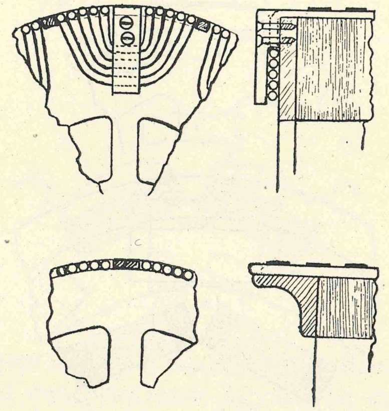


FIG. 1—SURFACE WOUND ARMATURE WITH RADIAL CLAMPS (UPPER) AND WITH AXIAL CLAMPS (LOWER)

ated poles with these machines in order to avoid excessive field heating.

The self-induction of the armature windings on these machines was very high compared with the old surface-wound armatures and therefore, in order to obtain passably good regulation, fewer armature turns had to be used, with correspondingly higher inductions, and this made the use of solid poles impracticable on account of heating. Furthermore, on account of the overhanging tooth tips, the small air-gap and the high induction per pole, this early type of toothed armature was very noisy. In one instance, it was credibly reported that one of these machines could be heard two miles away on a quiet night. However, several machines of this construction were put out by the Westinghouse Company, and operated for many years.

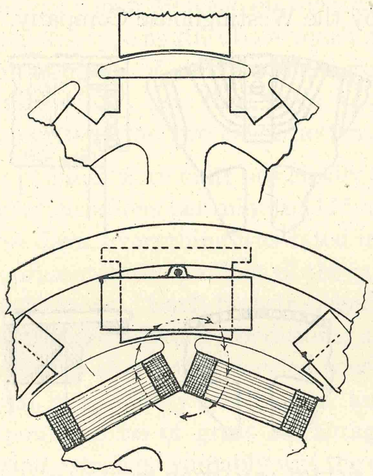


FIG. 2.

Meanwhile, the possibilities of the toothed armature construction in the old cast iron field were being given consideration. The writer made a special study of this matter, and finally decided that, in order to make this construction possible with solid cast iron poles, it would be necessary to work at relatively low inductions per pole, and with a very large air-gap, (fully as large as on the old surface-wound machines) and with a shape of tooth tip which did not have such great width compared with the pole tip as shown in Fig. 2. This meant that a pole tip and air-gap as shown in Fig. 3, should be used. With this arrangement, the armature self-induction would still be relatively high, and the regulation correspondingly bad, necessitating some form of compounding for regulating the voltage, similar to the compounding of a direct-current generator. This armature construction was worked out in detail for a 37.5 kilowatt field (that is, for the standard field of the 37.5 kw surface-wound type of machine). The armature teeth were similar to those in Fig. 3, in shape, and the air-gap or clearance from iron to iron, was made 3/8 inch on each side of the machine. The field was also compounded. When this machine was put on test, it was found at once that it could be loaded to 60 kilowatts without undue heating of the armature and field iron, and the problem of perfecting this machine then became one merely of increasing the amount of armature copper to carry the current at the 60 kilowatt rating. This, therefore, represented a big step in the development of the American type alternator. It was found that all the other Westinghouse standard cast iron machines of the rotating armature type could readily be changed in line with the above improvement.

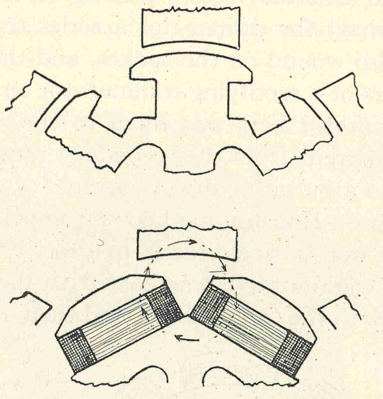


FIG. 3.

Compounding Alternators

The compounding of the 60 kilowatt machine was not a new feature, for already some of the laminated field toothed-armature type of machines had been compounded, in order to improve their regulation. Two different methods of compounding alternators had been developed by the Westinghouse and Thomson-Houston Companies, respectively. In the Westinghouse armature construction, the armature discs were punched in single pieces, with spokes, and were threaded directly on the armature shaft, no spider being used. This construction is illustrated in Fig. 4. In the assembled armature, the spokes were therefore of laminated material. These laminated spokes were utilized as the core of a compounding transformer. One lead from the armature winding was carried around the spokes of the armature before passing to the collector ring. This winding formed the primary of a series transformer. The secondary was also wound on the spokes, and the two ends were carried to the bars of a rectifying commutator on the shaft. The number of commutator bars was equal to the number of poles. The alternating current from the secondary winding was by this means changed to a pulsating direct current.

In the Thomson-Houston method of compounding, the main armature current was carried directly to a rectifying commutator, and, after being commutated, was passed to the field-compound winding, and back to the commutator, and then to a collector ring.

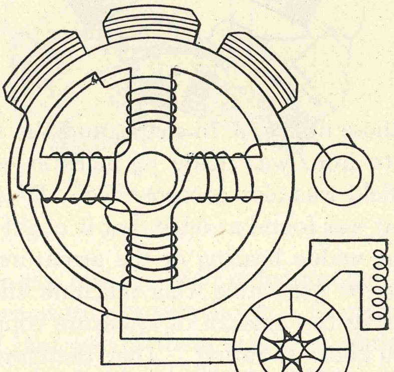


FIG. 4—SKETCH OF COMPENSATED TYPE OF WINDING

The main armature current therefore passed directly through the field, while in the Westinghouse method the secondary current from a series transformer was passed through the field. Both methods represented series compounding, and gave practically equal results, but there was much discussion as to the merits of the two methods. Both of these methods delivered pulsating direct current to the field winding. There was considerable inductive e. m. f. set up in the field windings by this pulsation, and this tended to cause inductive discharges across the rectifying commutators. In the Thomson-Houston method this trouble was overcome to a considerable extent by the use of a non-inductive shunt in parallel with the rectifying commutator, i.e., across the compound winding. In the Westinghouse method a similar result was accomplished by saturating the series transformer (or armature spokes) to such a high point that the inductive kick from the field could readily discharge through the secondary winding of the transformer without giving high enough voltage to flash across the commutator.

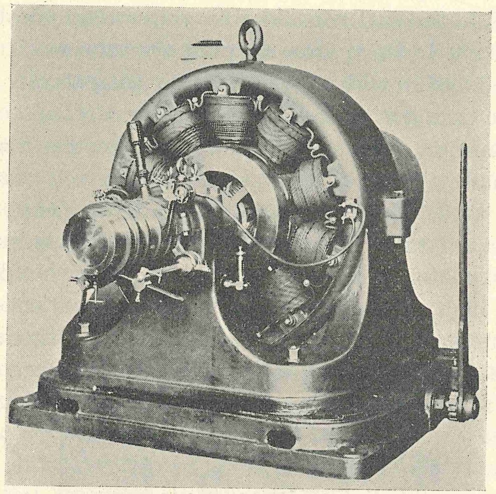


FIG. 5—EARLY WESTINGHOUSE 60 KILOWATT ALTERNATOR WITH COMPENSATING WINDING

The details of this method of compounding have been gone into rather fully, as this compounding was, at that time, an important step in our progress. The fact that of all these machines were built for single phase, allowed us to use such compounding. With the advent of polyphase generators, such methods of compounding soon disappeared, principally for the reason that a great majority of the early polyphase machines handled separate single-phase loads on the different phases, and it was not practicable to compound for these independently.

The above toothed type generator came into use about 1890 and lasted for several years, or practically until polyphase generators actually came into fairly general use before true polyphase loads became common. These toothed type generators allowed the use of relatively high voltages, as far as the armature winding was concerned, so that 2200 volts became comparatively common, and even 3300 volts or higher was used in some cases. In fact, the limit in such machines appeared to be at the collector rings, rather than in the armature winding.

Something may be said regarding the type of winding used on the armatures of these machines. In the Westinghouse construction the armature coils were machine-wound and taped before placing on the armature core. Each coil was made wide enough to slip over the top of the armature tooth, as shown in Figs. 6 and 7. This made the coil considerably wider than the body of the armature tooth, so that, after slipping over the tooth top the coil had to be reduced in width by special clamping tools. Supporting wedges were then driven in between adjacent coils.

Something may be said regarding the temperatures of these early alternators, both of the surface-wound and of the toothed types. In those days temperature measurements were very crude compared with present practice, which is admittedly still only approximate. In some of the surface-wound armatures excessively high temperatures must have been encountered in many instances, judging from the appearance of the insulation on the individual wires, after a year's service, for instance. However, it was difficult to obtain reasonably correct temperature of the armature windings, for the actual temperature of the conductors was undoubtedly reduced very greatly before the armature could be brought to a standstill. Even after this, temperature rises of 50 or 60 degrees C. were not considered as excessively high. Without doubt, some of these early machines, at times, attained actual internal temperatures of 120 to 130 degrees C., or even higher, with insulation on the conductors consisting of untreaded cotton fibre. No overloads were possible, for each size of machine was rated in as many "lights" as it could carry on a shop test without breaking down. The first few minutes, while starting up a new alternator in the testing room, were always anxious ones for the operators, especially so if any "improvements" had been made on the armature winding. Any defect in winding, or wrong connection usually resulted in a stripped armature and much flying copper. If nothing happened within the first few minutes after the machine was put on load, the attendants all came out from behind posts and other protections and went on with their work.

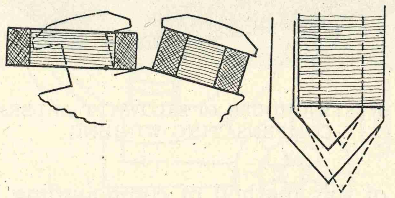


FIG. 6—SKETCH SHOWING METHOD OF PUTTING MACHINE WOUND COILS ON THE POLES

When the toothed armature came into use the above conditions were much alleviated. Defects in construction, or short-circuits, could not strip such armatures, and thus the danger and excitement were removed. However, it was found that the first short run did not tell the story of excessive heating as promptly as in the case of the surface-wound type. Experience showed that the toothed construction apparently could stand a severe shop test and still go wrong under similar loading within a short time after being installed. It was found that a given size of conductor would not carry as much current in the concentrated coils of the toothed construction as was the case in surface-wound coils. However, the method of testing the temperature did not show this, as the main part of the toothed armature coil was so embedded and so covered with insulation that the thermometer readings did not indicate nearly the true temperatures. The size of wire and the amount of copper in the coils then had to be increased until the machines did stand up in service. The true explanation of the discrepancies was not well understood at that time. In these toothed alternators, as in the surface-wound machines, the first machines were rated in "lights," but gradually the kilowatt rating came into use and became standard practice.

Introduction of Polyphase Alternators

In 1892 and 1893, polyphase alternators began to be considered seriously. In 1889 and 1890, a few such alternators had been built for the operation of Telsa induction motors. These early polyphase alternators were of the surface-wound, rotating armature type. These machines were very special in construction, and, like the Telsa motors, did not find much of a market. However, in 1892 and 1893, it began to be recognized that the best way to encourage the development of the induction motor would be by creating a demand for it, and it was decided that a good way to create a demand would be by encouraging the general adoption of polyphase alternators and supply circuits, with the idea that, when a suitable supply circuit was available, there was eventually bound to be a demand for motors to operate upon such circuits. With this general policy in view, there was great activity in the development of polyphase generators. This very quickly led to a very considerable departure in armature construction from the usual toothed armature as used in single-phase machines. The polyphase winding, requiring two or more coils per pole, naturally tended toward the slotted armature construction with two or more slots per pole. It was soon recognized that, in general, the larger the number of slots per pole and the smaller the number of conductors per slot, the better would be the general characteristics of the machine, so that the construction naturally tended toward the modern slotted type. Moreover, practically all the development in polyphase alternators was at relatively low frequency, compared with former practice. It so happened that there had been a well-defined tendency toward lower frequency in the period from 1890 to 1892. This tendency was largely independent of the induction motor problem for, at the time it became most pronounced, there was no true induction motor problem. It was becoming recognized that 125 to 133 cycles per second was too high for certain classes of work and for engine type generators, and that, in general, a very considerably lower frequency must eventually be adopted. A great many lower frequencies were tried by the different manufacturing companies, ranging from 50 to 85 cycles. However, 60 cycles seemed to have the preference at the time polyphase alternators began to come in.

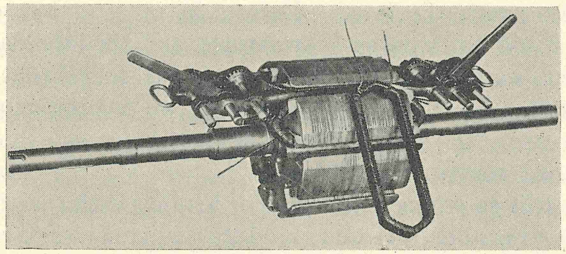


FIG. 7—VIEW OF ARMATURE IN PROCESS OF PLACING COILS AND CLAMPING THEM INTO SHAPE IN THE SLOTS

The early polyphase generators were mostly of the rotating armature type, and usually with a fairly large number of slots per pole. One notable exception was the "monocycle" machine which usually had only two slots per pole, one large slot for the main armature winding, and one smaller slot for the so-called "teaser" winding. Also, the early two-phase alternators of the "inductor" type, built by the Stanley-Kelly Company, frequently had only two slots per pole. However, it may be said that, from 1893 to about 1898, the great majority of the American built alternators were of the rotating armature type with distributed armature windings. The principal exceptions were the Stanley inductor type of machines and a few special "rotating field" machines, as distinguished from the inductor type.

The rotating armature machines were usually of 1100 or 2200 volts, although a few of considerably higher voltage were constructed. A few cases may be cited where special constructions were used. For instance, the principal lighting plant at the Chicago World's Fair in 1893, consisted of a large number of Westinghouse "twin" type generators. Each unit had two single-phase, standard toothed type armatures side by side on the same shaft. The teeth of the two armatures were staggered 90 electrical degrees with respect to each other, so that the two together could deliver currents having 90 degrees relation to each other. The object of this construction was to obtain polyphase current with standard single-phase types of machines without any radically new development. This type of unit did not persist and, in fact, was simply an expedient for this particular occasion.

THE FIRST NIAGARA GENERATORS

Also, in 1892 and 1893, the first large Niagara electrical development was worked out. The advisory engineers of this plant proposed 5000 horse-power generators, having stationary internal armatures and rotating external fields to obtain large flywheel capacity. In fact, the construction was not unlike the usual rotating armature machine of that period, as far as general appearance of the armature and field cores and windings were concerned. However, the method of supporting and rotating the heavy external field at a speed which, at that time, was considered excessively high, required an "umbrella" type of field support, which gave these machines a distinctive appearance. This type of construction did not persist, although these early machines are still in operation.

A further distinctive feature in these first Niagara machines was in the frequency employed. A speed of 250 revolutions per minute was decided upon. The engineers of the power company proposed eight-pole machines, giving 2000 alternations per minute or 16 2-3 cycles per second. The Westinghouse Company proposed, as an alternative, 16 poles, giving 33 1-3 cycles, the advantages claimed for this frequency being that it was better suited for motors and rotary converters, which were then promising to become of importance. One advantage claimed for the 16 2-3 cycle machine was that it would permit the use of commutator type alternating-current motors. After much discussion, and weighing and balancing of all the various arguments for and against these two frequencies, it was finally decided to use 12 poles, giving 3000 alternations per minute, or 25 cycle polyphase current and, as far as the writer knows, this was the origin of the present 25 cycle standard.

Considering what a radical departure from ordinary construction was made in these first Niagara generators, it is self-evident that many curious and interesting conditions developed during their design, construction and tests. As far as the writer knows, these were the first large alternators which were deliberately short-circuited at their terminals when running at full speed and at normal field charge. There were no instruments available to measure the first current rush, but it was obvious that this current was far greater than the steady short-circuited current of the machine under similar field charge, for there were ample evidences of a terrible shock at the moment of short-circuit. It was suspected at that time that the first rush of current was only limited by the armature impedance, and not by the so-called synchronous impedance which fixes the value of the steady short-circuit current.

This also was the earliest machine of which the writer predetermined the field form and wave form by analysis of the flux distribution. Later, when making shop tests on one of these machines, the e. m. f. wave form was measured directly by rotating the field at normal field charge at such an extremely low speed that a voltmeter connected across the armature terminals showed such gradual variations in e. m. f. that readings taken at regular intervals could be plotted to form the voltage wave. Slow rotation was obtained by means of a steel cable wrapped about the outside of the external field and with one end of the cable attached to a small diameter spindle around which it was wrapped at a very slow rate. This was a very crude method, but the wave form thus obtained checked very accurately with tests made some years later.

Also, the early Niagara machines embodied one of the first distinct attempts to ventilate alternators artificially. Early belted machines had had small ventilating bells on each end. But these Niagara machines were designed primarily with a view to setting up an abnormal air circulation by means of special "scoops" or ventilators on the umbrella supports. Very much thought and discussion were given to this subject of artificial ventilation. The results of our tests led to the arrangement of the scoops so that they acted as exhaust pipes.

Also, water cooling of the armature spider was tried on some of these early machines, but proved ineffective, due to the fact that the cooling medium was applied too far away from the point of development of the larger part of the armature iron and copper losses.

INFLUENCE OF DIRECT-CURRENT DESIGN

It must be kept in mind that the general trend of direc-current development had a certain influence on alternating-current generator work. For example, there had been a slow, but positive tendency in direct-current generators, toward the engine type construction. Also, from 1890 to 1893, direct-current generator armature construction had changed from the surface wound to the slotted type. This doubtless had some influence in changing alternator design toward the slotted type, especially when the polyphase type of windings came into use. Also, there was a pronounced tendency toward the engine type, slow speed alternator, accompanying direct-current practice. Practically all of these early engine type alternators, except the inductor type, had rotating armatures. Meanwhile, an interesting development took place in the armature construction of some of these machines. In most of the smaller belted machines, open armature slots were used with machine-wound armature coils. However, many of the early larger machines, especially of the engine type, were built for relatively low voltage, such as 440 volts, two or three phase. This admitted in many cases of simple bar windings with one or two conductors per slot. This allowed partially closed armature slots with shoved-through straight conductors, and bolted-on end windings, giving a very strong substantial type of winding for resisting the rotational stresses. The partially closed slot became a sort of standard in Westinghouse machines, and endured for a number of years, and was even carried into the stationary armature type of machine when rotating fields came into general use. This partially closed slot arrangement was a very good one as long as the generator voltages were relatively low. The same may be said of the rotating type of armature as a whole. However, when high voltages came into more general use, a different construction was preferable.

In reviewing the period of the rotating armature, slotted types of machines, the monocyclic system should be briefly described. Apparently this was gotten out with the idea that it avoided the patented features of the Telsa polyphase system. The armature circuits on this monocyclic system were so arranged that, when carrying load, one phase carried nearly all of the energy load, while both phases supplied magnetizing current for the operation of induction motors. During the period when this machine was in vogue, single-phase lighting work represented the principal service, while induction motor loads were relatively small. With increased use of polyphase loads, and with the elimination of the patent situation, the monocyclic system gradually dropped out.

It was early recognized that a stationary armature winding would be an ideal one in some respects, but it was thought that any rotating field construction was bound to be a difficult and expensive one. The inductor type construction was supposed by some engineers to overcome the objections to the rotating field, but many others considered that this type was not a final one, as it did not use the magnetic material in the machine to the best advantage. In the earlier alternators, with insufficient ventilation through the armature core, relatively low magnetic densities were necessary to avoid excessive iron heating, and the inductor alternator, with its non-reversal of armature flux, was worked at almost double the induction of the rotating armature type of machine, and thus the disadvantages of the non-reversal of flux of the inductor type were masked. In other words, the inductor alternator waas worked well up toward saturation, while the other types were worked at only about half saturation. However, with improvements in ventilation due to radial ventilating ducts, improvements in iron by better annealing and painting of the laminations, etc., the flux densities in the rotating armature machines were gradually increased until high densities, approaching saturation, were reached. A corresponding increase in flux densities in the inductor type was not possible, on account of saturation. Therefore the rotating armature type of machine, in the later designs, was much more economical than the inductor type, although the latter had a very considerable advantage, especially at high voltages, in its stationary armature construction. Due to the merits of the stationary armature construction, the present rotating field type of machine was gradually evolved, which possesses the advantages of the stationary armature of the inductor type machine and the reversing flux of the rotating armature alternator. It was the development of this type of machine which sounded the death-knell of the inductor type. However, the Westinghouse Company, about 1897, decided to bring out a line of inductor type alternators to meet market conditions, although such decision was contrary to the recommendations of the designing engineers of the company, whose recommendation in particular was in favor of the rotating field construction as a more permanent type. However, as the rotating field type was not yet established, except in a very minor way, and as the inductor type had been on the market for years, it was decided to build the inductor type, although the design adopted was somewhat different from the Stanley type. Three sizes of these machines were built, two belted and one engine type, but the inductor type, as a commercial proposition, soon died out.

One of the interesting peculiarities of the inductor type alternator, as usually built, was in the enormous stray field appearing in the shaft, bearings, bedplate, and sometimes in the engine-governing mechanism in engine type units, necessitating in at least one case, the use of brass governor balls. In the usual construction of inductor alternator, there was but one exciting winding. The magnetic circuit and the field winding were arranged as in Fig. 8, which shows both the Stanley and the Westinghouse constructions. The normal or useful path of the magnetic flux is indicated by the dotted lines a, a. Obviously, the field coil which set up flux through these paths could also send magnetic fluxes through the shaft, bearings and bedplate along the dotted lines b, b. Moreover, if the two bearings were not connected by a magnetic bedplate, as might be the case in engine type machines, then, in two-crank engines the engine cylinders and other parts became opposite poles of a very powerful electro-magnet, when the field coil was excited. The stray magnetic field set up in engine type units was sometimes so strong as to interfere with the governing mechanism. Also, with a strong unidirectional flux between the bearings and shaft, each bearing became part of a small unipolar generator, of which the bearing surfaces formed the brushes. In some machines, quite heavy currents were generated in the bearings, sufficient to "eat away" the bearing surfaces or to pit them so that bad bearing operation resulted. As this was primarily a magnetic trouble, insulating the bearings from their pedestals would not stop the action. To overcome this trouble, the Stanley Company added a "bucking" coil placed around the shaft at one side of the generator, this coil being in series with the main field winding and magnetizing in the opposite direction. The ampere-turns of this bucking coil being made equal to those of the field coil, the resultant ampere-turns between the two bearings would be zero. Obviously, in an alternator with a bedplate and two bearings in which the armature frame rested directly on the bedplate, a single bucking coil at one side of the machine would not neutralize the stray field through both bearings.

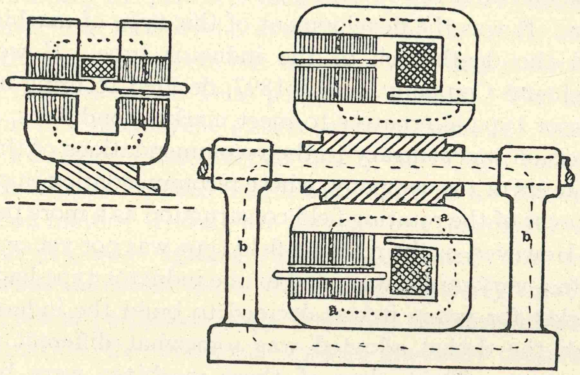


FIG. 8—SKETCH OF MAGNETIC CIRCUIT OF AN INDUCTOR ALTERNATOR

Rotating Field Generators

Considering next the rotating field type of machines, possibly the earliest example was the Niagara type, mentioned before. This had an internal stationary armature, with windings on its outer periphery like the ordinary rotating armature. Outside this was the rotating field, consisting of a heavy forged steel ring with inwardly projecting poles. However, this type of construction was relatively expensive, and was never adopted generally. The more modern rotating field type of alternator, with external stationary armature, was a rather gradual development and, during this period, there was much heated discussion as to the relative advantages of the rotating field and rotating armature types. The rotating field gradually superseded the rotating armature construction for a number of reasons, the principal one having to do with the armature windings and voltages. In the rotating armature, the end windings were more difficult to support than in the stationary armature. Also, with the gradual advent of higher voltages, the stationary winding proved to be far superior. However, as a goodly proportion of the alternators built during this transition period were of the engine type and for low voltage, in which heavy bar windings could be used, (such being conditions under which the rotating armature made its best showing,) this type persisted for several years after the rotating field type became commercial. Gradually increasing voltages, however, necessitated the use of stationary armature machines, for at least part of the business. The manufacture of two types of apparatus for the same general purpose could not persist, and eventually that type was adopted exclusively, which allowed both high and low voltages. By 1900, the rotating field alternator had come into very general use, and the rotating armature type was disappearing. This rotating field type has persisted until the present time, although many minor modifications have been brought out from time to time, due largely to change in speed conditions, etc.

In the rotating field development, the tendency for a number of years was strongly toward the engine type construction and relatively low speeds in many cases. The construction was carried to the extreme, in some cases, where the usual flywheel capacity required for the slow speed engines was incorporated in the field structure of the alternator itself. In some cases, this meant enormously large machines for the output. A prominent example of this is found in the seventeen 6 000 kilowatt engine-type machines designed in 1899 and 1901 respectively, and installed in the Fifty-ninth and Seventy-fourth Street power stations of the Interboro Rapid Transit Company of New York City. As an indication of the changes taking place in the electrical field, it may be stated here that arrangements have been made recently to take out a number of these machines and install in their place 30 000 kw turbo-generator units. The existing engine type machines are probably in as good condition now as when first installed, and are being replaced simply because they occupy too much space in proportion to their output.

The rotating field alternator of the early days was not radically different from the rotating field alternator of today, the principal differences being in the type of armature windings, methods of ventilation, etc.

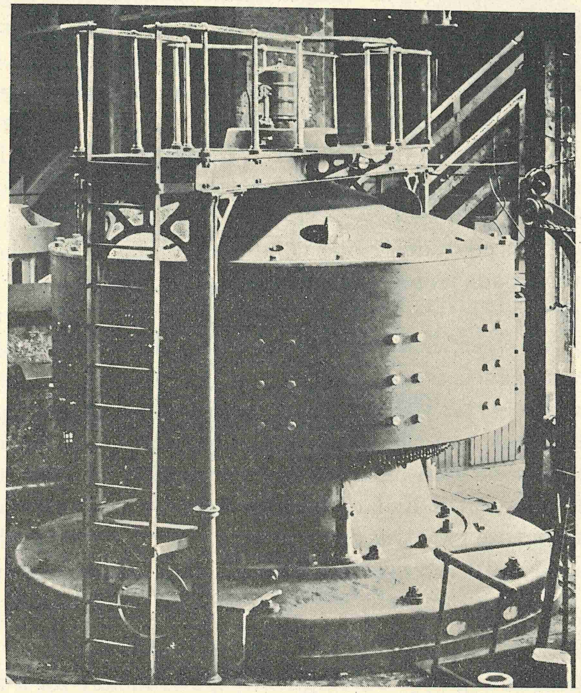


FIG. 9—SHOP VIEW OF 5 000 HORSE-POWER TWO-PHASE NIAGARA ALTERNATOR

Field Construction

In the types of field windings there has been but little change. In many of the old stationary field machines of large capacity, the field windings consisted of strap wound on edge, one layer deep. For smaller machines, either square or round wire was commonly used. In the latter rotating field machines, similar constructions are used. In the construction of the field itself, there have been some variations and modifications. In many of the older machines the poles were laminated as at present. The method of attaching the poles varied in different constructions. In many of the earlier Westinghouse rotating fields the laminations were punched with two or more poles in one piece, the poles having no overhanging tips, and the field coils being held in place by metal wedges between pole tips, fitted into notches or grooves at the pole tips, each pole being attached to the field ring or yoke by means of bolts or dove-tails. This latter construction possesses numerous advantages, in that cheap dies can be used, and the same pole punchings can be used for a number of different designs, in which either the diameter or the number of poles is varied.

Water Wheel Type Generators

With the advent of the turbo-generator on a large scale, the engine type rotating field alternator almost disappeared from the manufacturing field, except in the smaller size units. However, during this period there has been a gradual development in the use of water powers, and water-wheel driven generators have come into much greater prominence in the past few years. In this line of development, speeds and capacities, unheard of in the earlier days, have become accepted practice with the development of both high-head and low-head water powers. In the former the tendency has been toward very high speeds for a given capacity such

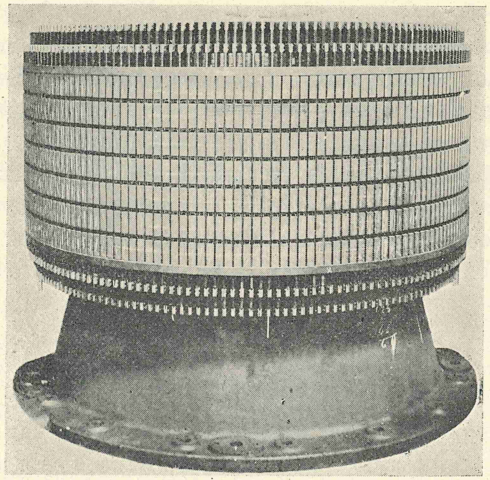


FIG. 10—STATOR OR ARMATURE OF NIAGARA ALTERNATOR

as the 17 000 k.v.a., 375 r.p.m., Westinghouse machines, built for the Pacific Light & Power Company, and the 10 000 k.v.a., 600 r.p.m., Westinghouse generators, built for the Sao Paulo plant in Brazil. Typical examples of low-head, slow-speed practice are found in the 60 cycle, 75 r.p.m., 96 pole, 2 700 k.v.a. Westinghouse generators for the Stevens Creek development, and the 25 cycle, 58 r.p.m., 52 pole, 9 000 k.v.a. General Electric generators for the Keokuk plant. The former are abnormal in the very large number of poles required for moderate output, while the latter are abnormal in the very low speed. Both of the above machines are of the vertical type, and are examples of a very pronounced tendency toward vertical machines, which has been apparent in the later water wheel practice.

On account of the high speeds of some of the modern rotating field alternators, mechanically stronger spiders have come into general use. Even in moderate speed units the usual high runaway over-speed of 100 percent has necessitated the use of very substantial spiders.

During the past few years, some very interesting spider constructions for the rotating fields of large high speed alternators have been built to meet the severe speed requirements. Some of these have been made up of cast steel centers or spiders with cylindrical rims built up of overlapping laminated punchings ,thoroughly bolted together and attached to the spider by dove-tails. The outer periphery of the laminated ring carries dove-tail grooves for poles. In another construction, the entire spider consists of thick rolled iron plates, bolted together, and with dove-tail grooves on the outside for the poles. In still other constructions, the rim of the spider consists of a heavy steel ring in one or more sections to which the cast spider is bolted. Usually with this cast rim the poles are bolted to the spider. In some cases the rim forms an integral part of the spider itself, being cast with the spokes and hub. The type of construction adopted in each case is, to a large extent, dependent upon the stresses to be taken care of, so that no one type seems to fit all cases to best advantage.

The Problem of Ventilation

In the later rotating field alternators the problem of ventilation has received much consideration, especially in the case of machines operating at abnormal speeds. In very high speed machines of very large output the armature and field cores have a ratio of width to diameter which is relatively much greater than in ordinary machines, and this has necessitated abnormal conditions of ventilation. Something may be said here regarding the general problem of ventilation of alternators and its influence on the evolution. Back in 1891 or 1892, radial ventilating ducts or passages came into use commercially on certain direct-current machines. The results being quite satisfactory, it was natural that alternators should have the same method of ventilation. The use of such ducts was in reality one of the great steps forward in the evolution of dynamo-electric machinery, although but little recognition has been given to this fact in electrical literature. The use of radial ventilating ducts has continued to the present time with little change except in the construction of the spacers themselves, which have been many and varied in design and materials. With the change from the rotating armature to the rotating field construction of alternators this feature was retained in full. In some of the earlier Westinghouse rotating field machines the field structure also had numerous ventilating ducts, principally for the purpose of supplying ample air to the armature ducts. Also, about ten years ago, special ventilating end bells and vanes began to be used on rotating fields, in order to set up an extra air circulation through the armature end windings, etc., due largely to the fact that the slow-speed engine-type machines of that period did not have much natural blowing action. Following this, and partly as an outgrowth of turbo-generator enclosing, came the semi-enclosed alternators, mostly for high-speed water-wheel driven units, and this practice is not uncommon at present.

The proper ventilation of an alternator or, for that matter, of any dynamo-electric machine, is very much of a problem, for no two cases, in different sizes or types of machines, are quite alike. The problem lies first, in furnishing the proper quantity of air to carry away the heat developed, and in then distributing such air in proper proportion through the complex multiple paths in the machine. The proper distribution of the ventilating air is usually the most serious part of the problem. The present solutions of the problem are based largely upon past experience, and no really workable rules have yet been developed. In arriving at the present practice many disheartening experiences have been undergone by all designing engineers. The writer has known many cases where totally unexpected results, both good and bad, have been developed and, in some of these cases, no logical explanation was forth-coming, so that the results could not be taken advantage of, with any assurance, in future work. This has been one of the most discouraging features in the general problem of ventilation.

ARMATURE WINDINGS

Something might be added here on the subject of armature windings. There have been probably as many types of armature windings developed as there have been types of alternators. The windings for the earliest smooth body and the toothed armature constructions have already been described. In the early Westinghouse polyphase alternators, two-phase was used mostly, due principally to the fact that single-phase lighting circuits formed the principal load, and, with two-phase machines, there were only two circuits from a machine instead of three circuits with the three-phase winding. Moreover, many of these very early polyphase alternators were used in reality as straight single-phase machines, taking current off one phase only. For this purpose a closed coil armature winding, like that of a direct-current generator or rotary converter, with four taps for taking off the two phases, gave about the most economical type of winding, as far as armature copper losses were concerned. When such an armature is used for single-phase it can deliver seven-tenths as much output as a single-phase machine as it can give two-phase with the same total copper loss per coil. It was partly for this reason that many of the early Westinghouse polyphase machines had a single closed coil winding. Another reason for such winding was that there were no definite phase groups and no high potential between phases. Furthermore, the arrangement of the end windings was such that the coils tended to interlock and support each other, thus assisting in resisting centrifugal forces. This winding was used mostly for two-phase machines, but was also used to a considerable extent on three-phase armatures.

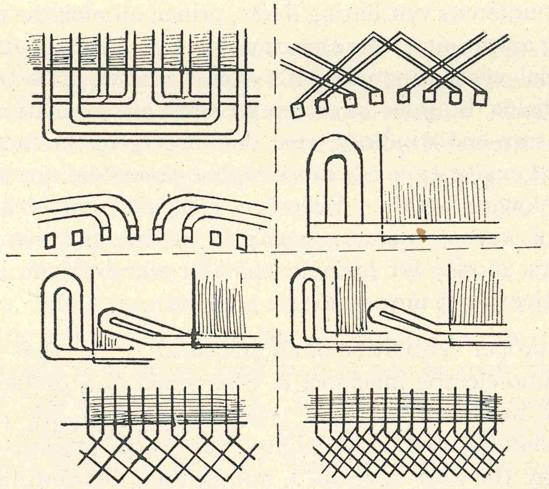


FIG. 11—VARIOUS TYPES OF EARLY STATIONARY ARMATURE WINDINGS

With the advent of the rotating field type of machine, this closed coil type of armature winding was not used to any great extent, open-coil two-phase and star-connected three-phase taking its place. Delta-connected three-phase was used in very rare cases, as there was danger of circulating current with such windings.

In the construction of armature windings possibly more radical changes have taken place than in the types of windings. Many of the larger low speed rotating armature alternators had bar windings with separate end connectors, soldered or bolted on. Many of the earlier stationary type armatures had either built-up bar or strap windings, or concentric type windings in which each phase winding was arranged in a concentric group, and the groups of the different phases overlapped each other. Some of these were made with partially closed slots and others with open slots. The built-up bar or strap windings were frequently of the partially closed slot type, while the concentric windings were more usually of the open slot type. Gradually, however, both these types of windings were superseded by the "duplicate coil" type of winding, similar in appearance to the usual direct-current armature and induction motor primary windings. This later type of alternator winding was arranged in two layers of coils at the ends, in either one or two layers in the slots. The two-layer, two-coil per slot arrangement is now practically the standard. These types are illustrated in Fig. 11.

In the rotating field machines, partially closed slot construction was carried to comparatively high voltages. For instance, the 6 000 kilowatt, 75 r.p.m., 11 000 volt, three-phase generators built for the Manhattan Elevated Railway in 1900 had three bars side by side, in each slot, with soldered-on end connectors.

As the partially closed slot and the open slot constructions are radically different from each other, something should be said regarding the reasons which prompted the use of either type. As already indicated, the partially closed slot type came in with the larger rotating-armature low-voltage alternators in which bar windings could be used. This construction gave good mechanical support for the bars in the slots, thus avoiding the use of bands. Moreover, with the very narrow slot openings at the top of the slots, there was very little "bunching" of the magnetic flux at the armature tooth tips with the consequent low pole face losses, even with very small air-gaps, and high gap flux densities. The disadvantages of the partially closed slot is found largely in the type of windings required.

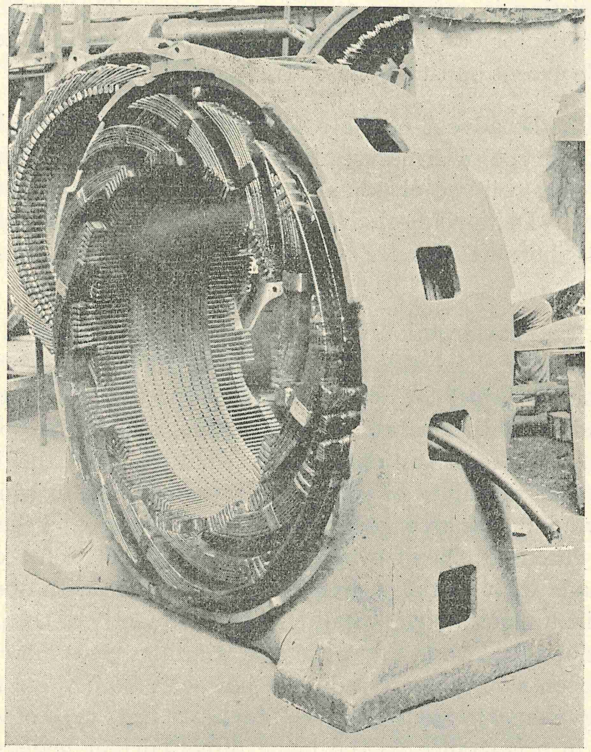


FIG. 12—BAR AND END CONNECTOR TYPE OF WINDING WITH PARTIALLY CLOSED SLOTS

In these early machines, it was found practicable, in general, to use completely formed and insulated coils with such slots, and therefore, either hand windings or built-up types of windings were used. While these were possible and practicable in a manufacturing establishment, yet such types of windings are usually difficult to repair by the ordinary operator inexperienced in the refinements of armature winding. When it comes to repairs, the usual machine-wound coil, which is completely insulated before being placed on the armature core, is very superior but, in general, this type of winding requires an open slot construction. However, when the stationary armature construction came into general use, the advantages of the overhanging tooth tips in supporting the coils largely disappeared. There remained therefore the disadvantages of the flux bunching, against the advantage of coil construction, if open slots were used. However, the use of laminated poles, and the judicious proportioning of the air-gaps and flux densities, to a great extent eliminated the losses due to open slots. In conse-

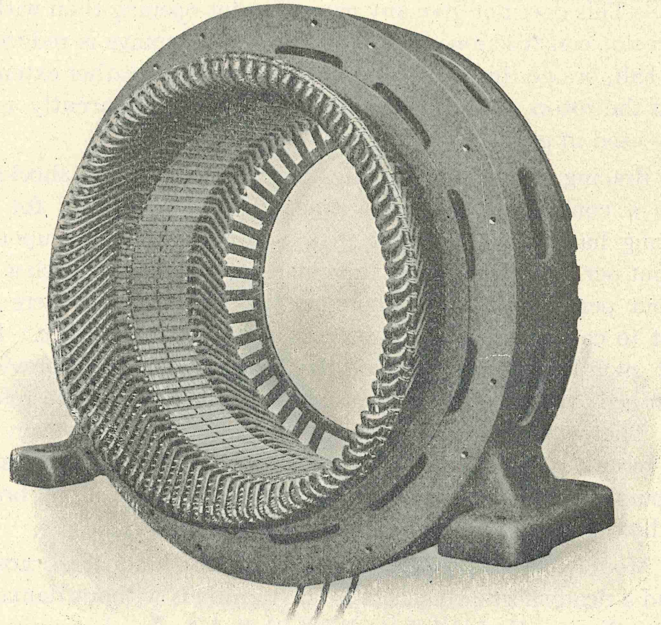


FIG. 13—DUPLICATE COIL TYPE OF WINDING, TWO COILS PER SLOT

quence, the open slot construction and the duplicate type of armature coil, have apparently come to stay, in this country.

Various attempts have been made to obtain the advantages of both the open and the partially closed slot arrangements. Probably all large manufacturers of alternators have tried some form of magnetic wedge, instead of the usual fibre or wood wedges which serve to retain the coils in the slots. Another arrangement is the equivalent of combining two or more open slots in one, with an over-hanging tooth tip, which covers the slot with the exception of the widths of one coil. Two or more completely insulated coils are fed successively into the slot opening and arranged side by side. This does not give any narrower slot opening than with the open slot construction, but the number of openings is reduced to one-half, or one-third. This construction is used rather extensively in the rotors of large induction motors, but apparently is but little used in generators.

Bracing of the end windings against short-circuit shocks has been a comparatively recent practice. The necessity for such bracing has been dependent to a considerable extent upon the output per pole, and the old time machine seldom had such a large output per pole that the short-circuit current-rushes were sufficient to cause dangerous distortions of the end windings. However, such bracing was used on the Niagara machines, previously described, and also on the Manhattan generators above referred to. These, however, were very rare instances. However, with the recent high-speed, high-output water-wheel generators, the outputs per pole have become such that some form of end bracing has become rather common.

Modern Westinghouse machines of this kind are braced to stand a dead short-circuit across the terminals without damage to the windings. Under this condition, these large machines may give a momentary current rush of from ten to twenty times the rated full-load current. However, the bracing required on the end windings of such machines is of relatively much less importance than on turbo-generators of corresponding capacity, due to the fact that, in the former class of machines, the end windings are relatively short compared with those of turbo-generators.

The above description brings us practically up to date, as far as the ordinary synchronous alternator is concerned. No description of the development of the turbo-generator has yet been given. This forms a rather distinct development which should follow at this point presumably, but it is thought advisable to interpolate here some description of the problems of parallel operation, e. m. f. wave form, regulation, etc., which came into prominence and were practically taken care of previous to the advent of the turbo-generator on a large scale.

Parallel Operation of Alternators

One of the great problems which developed in the operation of alternators was that of the parallel running of two or more units. At one time this was a very serious question, but in recent years, it is very seldom heard of. Considering the almost universal practice of paralleling alternators, which holds at the present time, one might be led to wonder why there ever was any trouble. Far back, in the days of the high-frequency surface-wound alternators, paralleling was attempted in many cases and, not infrequently, with considerable success. However, a failure in an attempt to parallel, in those days, usually meant the destruction of the apparatus. Those old time surface-wound alternators usually had very low self-induction, so that, in case of sudden short-circuit, an enormous current could flow, sufficient usually to strip the arm-

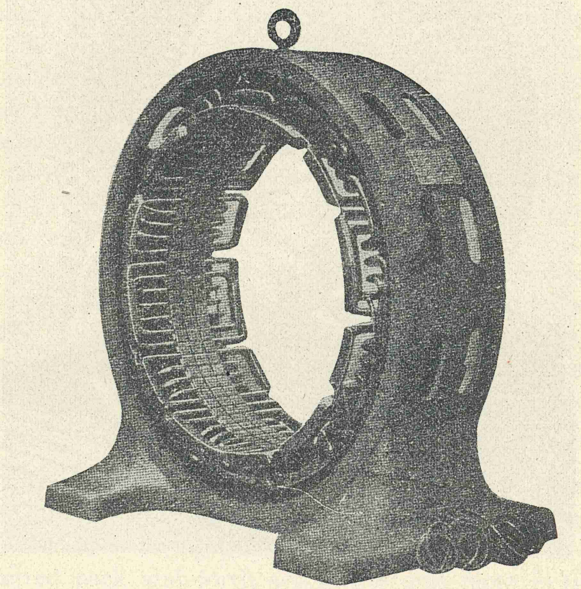


FIG. 14—DETAIL VIEW OF THREE-PHASE CONCENTRIC WINDING

ature winding from the core, by bursting the bands, or otherwise. A failure in an attempt to parallel two machines was practically equivalent to a short-circuit, and this usually meant destruction of the apparatus. However, if once paralleled successfully, the machines usually did not act badly. One favorable condition, not then appreciated, was that all these early machines were belt-driven. It may be said, however, that in those days parallel operation, while considered possible, was also considered more or less risky. In the period immediately following the surface-wound alternator, parallel operation was very much the exception, rather than the rule and, when engine-type alternators came into use, paralleling was considered for several years as very questionable. At this time the situation was as follows:—Belted alternators could be paralleled in many cases. Direct-coupled alternators, if flexibly driven, could be paralleled almost as well as belted machines, while direct-coupled or engine type generators, without flexible coupling or drive, could not be relied on to parallel without hunting. It thus became recognized that some flexibility between the generator and its prime mover was an important adjunct to parallel operation. This led to the consideration that the engine might be back of the difficulty in many instances, and it was then assumed that inequalities in the regular rotation resulting from insufficient flywheel or from hunting governors, tended to cause hunting in the generators. Investigation showed that such conditions did tend to produce hunting, but that the magnetic conditions in the machine itself would oftentimes maintain, or even accentuate, the hunting. Obviously, therefore, the trouble was both in the prime mover and in the generator. It was noted further that if the angular fluctuations in the driving power were relatively small, hunting usually would be very small, or would not be apparent at all. It was further recognized that, with belt or flexible drive, which tended to smooth out the speed fluctuations due to the prime mover, the hunting tendency tended to disappear. Attention was then turned toward improvement of the prime movers, especially in engine-type machines, in order to reduce fluctuations in angular velocity by means of heavy flywheels, and by means of dampers of some sort, such as dashpots, on the governing mechanism of the engine. Much improvement was accomplished in this way.

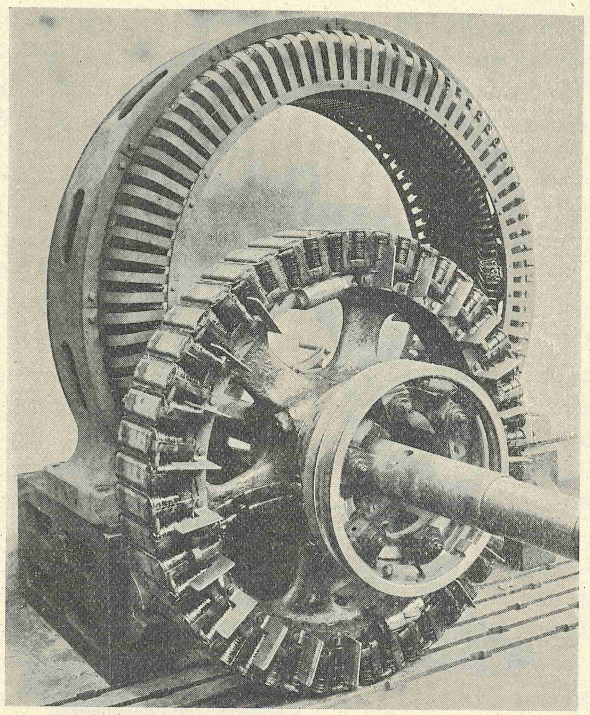


FIG. 15—75 K.V.A., THREE-PHASE, 60 CYCLE, 2 300 VOLT, 150 R. P. M. ROTATING FIELD ENGINE TYPE ALTERNATOR

THE INTRODUCTION OF DAMPERS

During this period many attempts were made to lessen the tendency of the alternator to maintain hunting. Investigation showed that, during hunting, the magnetic flux in the field poles shifted back and forth across the pole faces in time with the hunting, while such action did not occur when there was no hunting. This at once led to the theory that a low resistance winding on the pole face, or imbedded in the poles, would prevent or oppose this flux shift, and thus assist in overcoming hunting. However, about this time, rotary converters were coming into use, and it was found that, in such machines, hunting was usually more severe than in alternators, so that, in this country, the first true application of damping windings or devices to stop hunting were applied on rotary converters. It was also noted at this time that solid pole generators and rotary converters did not hunt to the same extent as did laminated pole machines, and it was correctly assumed that the solid pole faces gave an effect similar to that of low resistance damping windings. However, as it was desirable to use laminated pole tips, copper dampers on the poles gradually came into use. Some of these early dampers were very crude in form and type compared with present constructions. However, imperfections in the construction of the dampers were balanced to some extent by the large section of copper used and consequent low resistance. The earliest form of damper used in this country consisted of copper rings surrounding the poles and copper tips overhanging the beveled pole edges. This was the form most commonly used on converters. On alternators, in some cases the damper consisted simply of a low resistance ring around each pole. In still other cases the damper consisted of a heavy copper plate covering the pole face. This latter construction was only

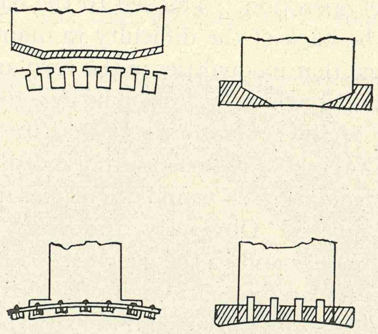


FIG. 16—VARIOUS FORMS OF DAMPERS

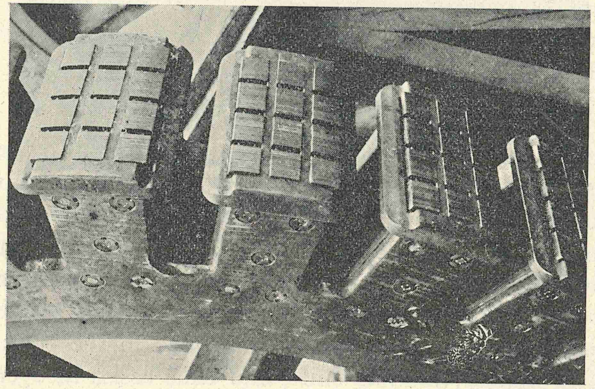


FIG. 17—GRID DAMPERS ON FIELD POLES

possible in machines with large air-gaps and very narrow or partially closed armature slots. These crude forms of dampers were gradually superseded by the so-called "grid" damper which consisted of a copper grid surrounding the pole and with ribs which lay in slots in the pole face. These various types of dampers are shown in Fig. 16. In very few cases were these old types of dampers so interconnected as to form a complete cage winding around the field.

Many tests were made at various times to determine the effect of interconnecting the grids on the different poles to form one complete cage. As a rule, there was no appreciable gain, and it was then assumed that such interconnection had no material advantages. However, it later developed that the reason why interconnection of the dampers did not improve the damping action very materially, was due largely to the very great amount of copper in those parts of the grid dampers lying between the poles. The grid damper was very effective, but was expensive in material, and was not easily applied on poles with overhanging pole tips. This type of damper was gradually superseded by one similar to the usual cage winding on the secondaries of induction motors, and this is the type which is in most general use at the present time. This construction has practically the same effectiveness as the old grid type, but is much more economical in material and, being placed in partially closed slots, it does not as greatly affect the iron losses in the machine, as was liable to be the case with the open slots, generally used with the grid damper.

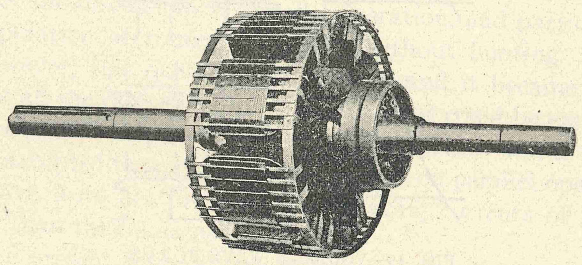


FIG. 18—CAGE WINDING TYPE OF DAMPERS

With the gradual introduction of dampers and improvements in angular rotation of the prime movers, hunting troubles in alternators practically disappeared, and parallel operation presented no difficulties, except under very abnormal conditions. Apparently these dampers or "amortisseurs," as they are sometimes called, were first proposed by the French engineer, Maurice LeBlanc, about 1891. However, they were "rediscovered" in this country by engineers who were not familiar with the above engineer's work.

VOLTAGE WAVE FORM

The e. m. f. wave form of alternating-current generators has been a matter of much discussion since the early days of alternator design. The old surface-wound machines gave a very close approximation to a perfect sine shape, due to the arrangement of the winding and to the very large air-gap. The first toothed armatures, with their very small air-gaps, gave e. m. f. waves which departed very widely from a true sine. In fact, this had about the worst wave form of any of the alternators which have been put out by the Westinghouse Company. Its shape was somewhat like that shown in Fig. 19, as would now be expected when the configuration of the armature tooth tips is taken into account. The later toothed armatures with large air-gaps and beveled tooth tips gave much better wave shapes.

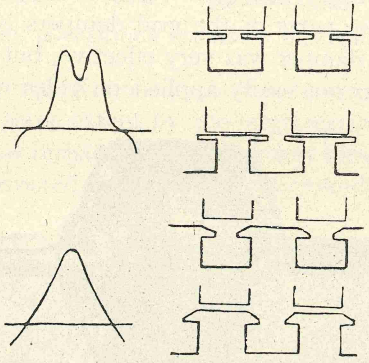


FIG. 19—VOLTAGE WAVE FORMS

Of early toothed armature machines and of later toothed armatures with larger air gaps and beveled poles.

With the advent of the true polyphase windings and the slotted armatures with several slots per phase per pole, fairly close approximation to sine shaped e. m. f. waves became common. In the first Niagara Falls 5 000 horse-power, two-phase alternators, the voltage wave was slightly flattened on the top due to the fact that the pole face width was somewhat greater than the width of each phase group in the armature. When very high voltages came into general use, and especially in machines with small pole pitch, the number of armature slots per phase per pole was reduced to a minimum in order to lessen the total insulation space. In extreme cases, but one slot per phase was used, giving but two slots per pole for two-phase and three slots per pole for three-phase. Such windings required special shaping of the field pole tips in order to approximate even roughly a smooth wave form of the sine shape. Later practice, however, has tended toward the equivalent of at least two slots per phase per pole, in order to obtain better results. Sometimes the desired result is obtained by the use of one extra idle or "hunting" tooth per phase.

In the early days of parallel operation of engine type alternators which, as described before, represented the most difficult conditions, great stress was laid upon the question of wave form in some of the discussions of parallel operation, and particularly, in the operation of rotary converters without hunting. Gradually, however, this question disappeared and it became recognized that all the cases of hunting encountered could be explained in some other way than by the e. m. f. wave forms, and it is now generally accepted that about the only effect on parallel operation due to wave form lies in possible circulating currents of higher frequency than the fundamental.

At the present time, a very close approximation to the sine shaped wave is considered preferable for general purposes, especially in transformation and transmission work. There have been some instances of telephone disturbances due to wave form but, as a rule, some local peculiarities of the distribution circuits have been involved in this trouble, for, in other cases, similar or even worse shaped waves have given absolutely no telephone disturbances.

REGULATION AND COMPOUNDING

Something should be said on the subject of regulation of alternators, for this is a very important characteristic, and has had considerable influence on types and designs. The old surface-wound alternators had extremely good regulating characteristics due to their low armature self-induction and low armature reaction consequent upon their large air-gaps. The writer does not know what value the current rose to, on steady short-circuit, compared with the normal rated current, but it was probably four or five times full load. The current rush on short-circuit was probably five times as great as the steady value. It is not to be wondered at that such armatures not infrequently wrecked themselves in case of a dead short-circuit. In the later toothed armature types, the armature self-induction and reaction on the field were very much larger, proportionately, than in the surface-wound machines. This, however, spoiled the regulation and some method of compounding was used, as already described. This compounding was common practice until larger capacity machines, especially the engine type, came into use. Even some of these latter were compounded by commutating the armature current (either directly or from a series transformer) and compounding the exciter field by means of the commutated current. A few of the smaller size alternators were both self-excited and compounded by commutating derived alternating-current circuits from the armature. This, however, was found to be very delicate, as the excitation and compounding were greatly affected by changes in the power-factor of the load, and by changes in speed.

One early attempt was made to compound single-phase alternators to correct for power-factor. In this case the commutated armature current was sent through the series or compound winding of the exciter. The brushes on the alternating-current commutator were so set that at 100 percent power-factor they were commutating about the middle of each voltage wave. In consequence, the current delivered to the brushes was not a true direct current but consisted of a double number of half waves, half of which were inverted, and the direct-current component of this commutated current was small and had but little compounding effect. However, with change in power-factor of the load, the phase of the current shifted, so that at some reduced power-factor, commutation occurred at the zero point of the current waves and the resultant current was all effective for magnetizing the exciter field. The total commutated voltage was very low and the commutator bars were shunted by a resistance so that there was no bad sparking, even when commutating at the middle of the current wave. This method did actually compound fairly well for change in power-factor, but the field for such method proved to be very limited, for compounding of alternators fell into disuse shortly after this.

The usual method of compounding on the early alternators was simple series-current compounding, just as in direct-current apparatus. Where the commutated current was supplied directly to the field compound winding, voltages of about 30 to 60 volts were most common at rated full load. With much higher than 60 volts, there was a liability of short-circuiting the compounding by arcing between bars on the commutator. There was also a liability of arcing or flashing when the phase of the current shifted due to change in power-factor.

When polyphase rotating armatures came into use, similar methods of compounding were resorted to. However, the secondary current was a resultant of the two, or three primary currents, for each of the primary phases was carried around the compensating transformer (or spokes of the armature) and the secondary winding carried a current in phase with the resultant of the primary ampere-turns. In the case of three-phase windings, the direction of one lead was reversed around the compensating transformer. Some curious conditions arose from the phase relations of the secondary current when parallel operation was practiced. It was necessary, when paralleling the main winding, to parallel also the compound winding. As the compounding current from each machine pulsated from zero to maximum value in each alternation, it was necessary to so parallel the terminals that all the commutated currents had zero value at the same instant, otherwise, the brushes on one commutator would, at times, short-circuit the current from the other commutator.

With the advent of larger belted machines, and of engine-type machines in particular, the compounding of polyphase machines was more or less unsatisfactory and was practically abandoned. To compensate for the lack of compounding, better inherent regulations were aimed at in the designs. This meant, primarily, machines which would give comparatively large currents on steady short-circuit, three to four times full load being rather common, and even six times full load being attained in some machines. The momentary current rush at the instant of short-circuit must have been excessive on some of these machines, due to their very low armature self-induction. However, due to the relatively small ampere-turns per pole, no very destructive distortions were found in practice. This characteristic of the short-circuit currents was carried into the rotating field construction, and even into the early turbo-generator work.

This practice of giving the alternators good inherent regulation was expensive in a number of ways, as it usually meant higher iron losses and less output than was possible otherwise, with a given size machine, or a given amount of material. Even at this early date, it was recognized that some form of automatic field current regulator which would maintain the terminal voltage constant, regardless of the inherent regulation would be a very useful piece of apparatus. Some form of regulation which would take care of change in power-factor, as well as load, was the aim of many designers. Among the different schemes brought out, the Rice method of compounding, brought out by the General Electric Company, is of interest. This was used principally with rotating field alternators. In this scheme, the exciter was usually placed on the same shaft as the alternator field, and, in such case, had the same number of poles as the alternator. The leads from the alternator armature were carried through the exciter winding in such a way that a lagging current, carried by the alternator, tended to strengthen the field of the exciter by shifting the armature reaction with respect to the exciter field poles. In this way a compounding action on the exciter was obtained which was practically in proportion to the demands of the alternator field with varying power-factor. In the case of engine-type machines of comparatively low speed, the exciter was geared to the alternator shaft, so that it ran at a considerably higher speed and the number of poles in the exciter was correspondingly reduced.

This method of compounding was effective, but the whole combination was apparently unduly complicated and expensive. Furthermore, it did not give the desired compensation under all conditions of operation, as it would not correct for changes in speed.

A later method of compensation for power-factor was devised by Alexanderson, and was used on a limited number of General Electric machines. In this scheme a derived current from the alternator itself was commutated in such a manner that compensation, proportional to the power-factor, was obtained. This was a purely self-excited alternator scheme and, like all self-exciting schemes in such apparatus, it was sensitive to speed changes, probably to a much greater extent than the Rice arrangement above described. A fundamental defect in all self-exciting compensated alternator schemes lies in the fact that stability of excitation is dependent upon having considerable saturation in the alternator magnetic current and, coincidently, if there is such saturation, the compound current has no direct relation to the load or power-factor. Thus such machines are either sensitive to speed changes, or their compounding is only approximate.

Following these schemes came the use of automatic regulators of which the Tirrill is best known. This regulator acts directly on the exciter field by short-circuiting a resistance in series with the field winding, the range of exciter voltage being controlled by the length of time the rheostat is short-circuited. Instead of cutting the resistance out in steps, which tends to give sluggish action in the fields, the Tirrill regulator cuts the whole resistance out each time, and the length of time is varied. This results in quick action. As the regulator tends to hold constant voltage at the alternator terminals, or on the line, change in power-factor or in speed does not modify the action. This type of regulator has proven very effective, especially in the case of alternators subjected to sudden and violent changes in load, power-factor and speed.

With the advent of larger alternator units, in proportion to the changes in load, the inherent regulation has been made relatively poorer, primarily because better machines otherwise are thus obtained. The short-circuit currents are reduced, and relatively lower iron losses, and lower temperatures or, higher outputs with a given temperature, are obtained. This has been carried further in turbo-generator design than in any other class of alternators, due partly to fundamental limitations in design. However, this poorer inherent regulation has proven to be of no practical importance, where suitable automatic regulators have been used with the machines.

One fallacy which was frequently found in the past, and which still persists to some extent, is that alternators should have equal inherent regulation to parallel properly. This is based partly on the feeling that the field currents of the alternators should vary over equal range when carrying their proper proportion of load, together with the knowledge that the variations in field current are dependent, to some extent, upon the inherent regulation. However, the fact that the shape of the saturation curve, in a given alternator, may have much more influence on the excitation, especially at high saturations, is usually overlooked.

TURBO-GENERATORS

The advent of the turbo-generator has had a predominant influence on alternator design. After the turbo-alternator once became established commercially in this country, it quickly revolutionized conditions by driving the large engine-type alternators out of the field. The evolution of all electrical apparatus has been comparatively rapid, but that of the turbo-alternator has possibly exceeded anything else in the electrical field. This evolution therefore merits a fairly complete description.

The first turbo-alternators built by the Westinghouse Company, were installed in the power plant of the Westinghouse Air Brake Company about 1898. These were three rotating armature machines of 300 kilowatts capacity, which ran at a speed of 3 600 r. p. m., giving 7 200 alternations per minute, or 60 cycles per second. They were coupled to Parsons turbines, built by The Westinghouse Machine Company. The Parsons Company in England had been building rotating armature alternators for a number of years, and the Westinghouse Company simply followed the Parsons' precedent. These first machines were operated for several years, but it was obvious, soon after their installation, that the rotating armature type of machine would not serve for

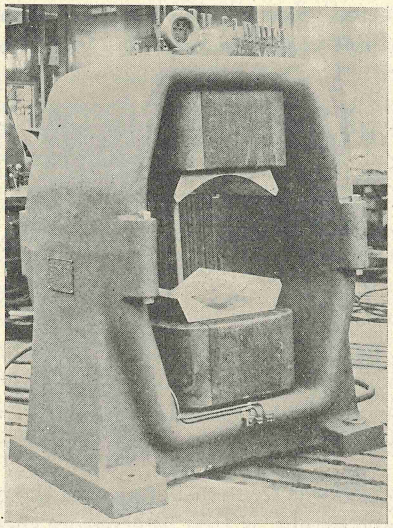


FIG. 20—FIELD OF EARLY ROTATING ARMATURE TURBO-GENERATOR

general turbo-alternator purposes. It was evident that, for voltages even no higher than 2 200, the rotating armature construction, at the necessary turbo-generator peripheral speeds, would become almost impracticable. Attention therefore was soon turned toward a 3 600 revolution, two-pole, rotating field type, and a very large number of possible constructions were considered. Finally one like that shown in Fig. 23 was worked out and built in 1899. This had the field windings completely embedded in a number of parallel slots, with supporting metal wedges at the tops of the grooves or slots. One machine of this type was built and tested. It operated in a satisfactory manner, except as regards windage and noise. The machine was not closed at the ends, like modern turbo-alternators, and thus any noise generated in the machine could be readily transmitted to the outside. The noise was caused largely by the two flat sides of the rotor. It was

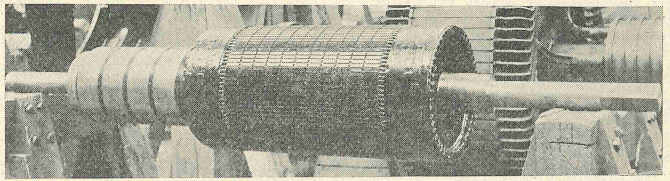


FIG. 21.—ARMATURE FOR TURBO-GENERATOR OF THE TYPE SHOWN IN FIG. 20

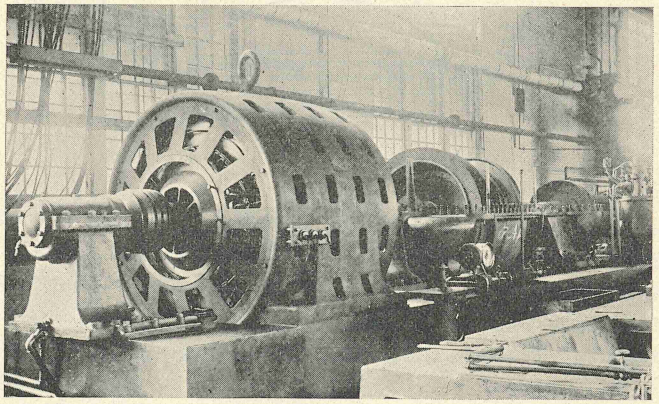


FIG. 22—1 000 KW OPEN TYPE TURBO-GENERATOR

so shrill and penetrating that it was very disagreeable to be around the machine, and was even painful to the ears after a short time. This construction was therefore abandoned temporarily, but after a few months it was taken up again and a new rotor was built which was entirely round, as shown in Fig. 24, but was otherwise very similar to that shown in Fig. 23. This new rotor, although noisy compared with modern machines, was so quiet, compared with the first construction, that it was immediately adopted as a standard construction. This is the now well-known parallel slot construction which has been used very extensively by the Westinghouse Company, although many very radical changes have been made in the constructive features of the rotor itself. This type of rotor was used originally only for the 400 kilowatt size at 60 cycles.

In the earlier machines of this type a number of very curious conditions developed. In the first machines the rotors were built of a number of thick discs or "cheeses" side by side, which were put on the shaft at high pressure. The two end discs were thicker than the others in order to accommodate the grooves in which the rotor end windings lay. The discs were made of high grade forgings. After some of these machines had been in operation for a considerable period it was found that some of the discs in the field core were traveling axially, i.e., quite appreciable gaps or spaces were showing between adjacent discs. In one instance they traveled to such an extent that the field windings were stretched longitudinally at the openings between the discs, until the conductors were actually attenuated to an extent visible to the eye. Obviously, the stretching force must have been enormous.

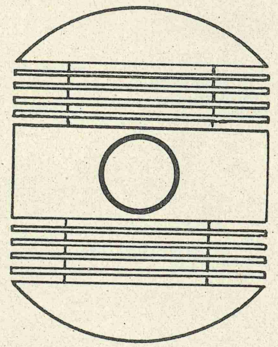


FIG. 23—EARLY TWO-POLE ROTATING FIELD

Eventually, the construction was changed on these two-pole rotors to a single disc of forged steel. Still later, steel castings were used quite extensively instead of forgings although, later still, the castings were abandoned in favor of forgings. There was much adverse opinion regarding the advisability of using castings for the 3 600 revolution machines, as some engineers held that they were more liable to contain flaws than would be the case with forgings. An interesting fact in connection with this is that, while a number of these early high speed machines "exploded," generally during runaways, yet in no instance was a cast steel field wrecked from this cause. This, however, does not constitute a proof of the superiority of cast steel, for it so happened that all the serious runaways were on machines with forged rotors. However, the record is a clear one as far as cast steel fields are concerned, for, of all the sizes and speeds of steel rotors which the Westinghouse Company has put out, not a single cast steel disc has burst. Present speed and output requirements have now carried the construction up to a point where special forged materials are the accepted practice.

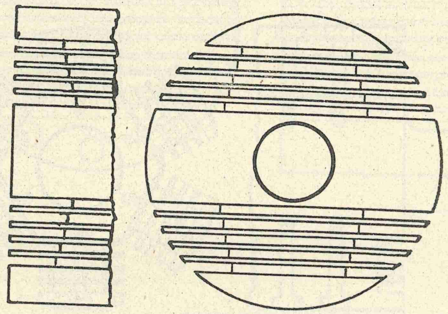


FIG. 24—ROUND TYPE TWO-POLE ROTOR

Soon after the two-pole, 400 kilowatt rotating field machine was put on the market, a four-pole, 750 kilowatt, 1 800 revolution machine was built. The rotor of this machine had four silent poles bolted on. These poles were provided with overhanging pole tips, and the field winding consisted of four coils wound with strap-on-edge. In fact, this first construction was very similar to the present type of rotor fields now used for other than turbo work. This construction proved difficult and expensive, but was applied to a number of six-pole, 1 200 revolution machines. However, the parallel slot construction used in the two-pole machines was so satisfactory that it was soon adopted for the four and six-pole machines, as shown in Fig. 25. In the six-pole machine it was not possible to make the poles integral with the central core, on account of the inability to machine the parallel slots in the sides of the poles, or to put in the windings. Therefore, separate poles were constructed, with parallel slots, and these were first wound and then bolted into place on the central core which, in this case, was made integral with the shaft. The four-pole machine was constructed for 750 and 1 000 kilowatts capacity, and the six-pole construction was made for 1 500 to 3 000 kilowatts.

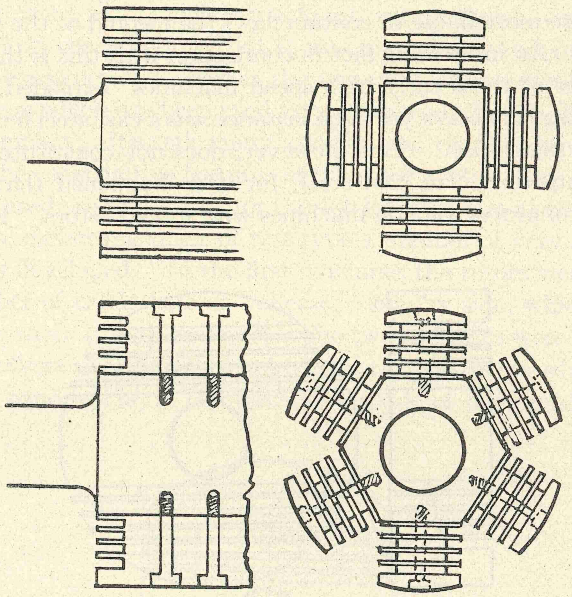
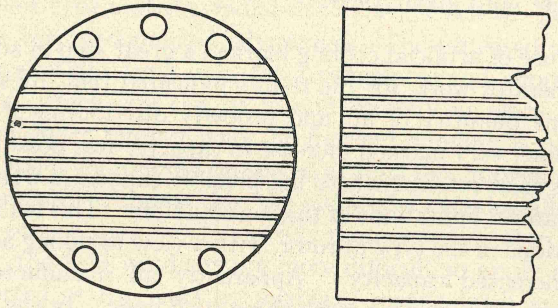


FIG. 25—PARALLEL-SLOT FOUR-POLE AND SIX-POLE FIELD CONSTRUCTION

Meanwhile, there had grown up some demand for moderate capacity 25-cycle machines at 1 500 revolutions. These were constructed along exactly the same lines as the two-pole, 3 600 revolution machines above described.

In this early work one order for four 5 500 kw, four-pole, 1 000 revolution machines was taken. This was entirely beyond the constructions undertaken before by the Westinghouse Company. The parallel slot type of rotor was adopted. An attempt was made to get forgings in a single piece large enough for these rotors, but they were found to be glass hard and brittle, except at the outer surface. As very large steel castings were frowned upon, it was decided to make these rotors of discs turned out of very thick steel plates, somewhat like the early 400 kw machines already described. Parallel slots were used as in the smaller four-pole machines. This construction proved to be feasible but was very expensive, and shortly after this, large cast steel discs were used, two discs side by side being used to form one rotor. This construction was satisfactory, and was used for many years.



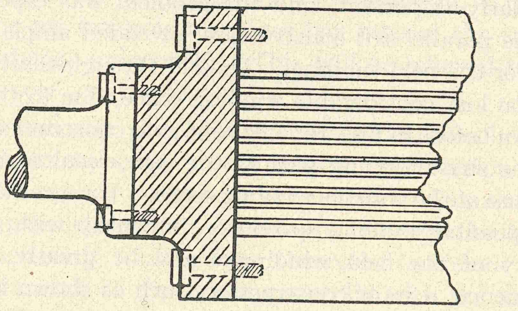


FIG. 26—TWO-POLE FIELD OF THE BOLTED ON CONSTRUCTION

Shortly after turbo-generators came into general use, there was considerable complaint regarding the noise due to windage. All these machines were equipped with some form of ventilating device, which either formed part of the normal construction of the rotor or consisted of some special blowing device at the ends of the rotor. Both the high speed and the large quantity of cooling air required, tended to make a noise which was very objectionable. A series of experiments with covers over various parts of the machines, showed that, by completely enclosing the two ends of the machine and by enclosing the field frame except at the top and bottom, (in a horizontal machine) the windage noise could be so deadened as to be practically unobjectionable. However, the tests also showed that artificial ventilation was necessary under this condition. This very quickly led to the practice of enclosing and artificially cooling turbo-generators, which practice has been maintained to this day. The first Westinghouse enclosed machines were built about 1903.

The use of artificial cooling marked a great step in advance in turbo-generator work, for the results indicated that, by supplying a sufficient quantity of air and properly distributing it through the machine, very marked increase in capacity was possible, and a point was soon reached where the possible capacities were beyond the mechanical limitations of the construction. This led to radical modifications in the type of rotor, with a view to taking advantage of the increased capacity. Apparently all manufacturers did more or less development work along such lines. In the Westinghouse constructions, the use of a thorough shaft was found to be one of the serious limitations, and this led to types of rotors without any through shaft. In the two-pole machines, this was particularly important, and the problem was especially difficult with the parallel-slot construction, provided ample space was allowed for the field winding. The old through-shaft two-pole construction lost considerable winding space, due to the shaft space, as shown before in Fig. 24. Attempts to construct such a machine with the shaft forming part of the core, resulted in still less efficient use of the possible winding space. It was obvious that if the whole possible winding space were taken up with slots, then the capacity of the field winding would be greatly increased. In consequence, a rotor construction, such as shown in Fig. 26, was designed and constructed. In this, bronze end supports or "heads" were bolted to each end of the field core, and the shaft proper was attached to these bronze heads. Bronze, or a similar non-magnetic material, was necessary to prevent magnetic short-circuiting of the field flux. This design was constructed and tested on a 1 000 k.v.a., 3 600 revolution machine, and then was built successively for 1 500, 2 000, 3 000, 4 000 and 5 000 k.v.a. machines, all at 3600 r. p. m. The same construction was also applied to two-pole machines of 25 cycles, up to 12 000 k.v.a. capacities. This construction of rotor has given an extremely good account of itself. However, it proved to be expensive on small capacity machines, as the bronze heads formed an undue proportion of the cost of material. For higher capacities of 3 600 r. p. m. machines, increase in capacity is obtained largely by increasing the length of the rotor core, and thus the bronze heads form a relatively lower percentage, and the construction becomes more reasonable in cost.

From the preceding, it may be seen that only two types of turbo-generators have been used very extensively, namely, the parallel-slot type and the radial-slot type. Each of these types has some very pronounced advantages. The principal advantage of the parallel-slot type is in the arrangement and support of the field coils. Each coil can be wound directly in place, with the conductor under tension, and the finished winding is completely encased, and is thoroughly protected against dirt, movement of the conductors, etc. Against this, the radial-slot machine allows more room for copper, and is magnetically more economical in material. However, the field windings are more difficult to apply and must be supported at the ends by auxiliary means, such as separate steel rings.

The enormous increase in output of turbo-generators, within very recent years, has made the electric and magnetic proportions of the rotors a feature of first importance in the design, so that the radial-slot type for two-pole machines has become the standard construction, almost universally. This will be referred to again under the four-pole construction.

While the two-pole parallel slot construction was being developed for larger capacities, the four-pole construction for 60 cycle machines has been pushed up to capacities of about 12 000 k.v.a. with the parallel slot, cast steel rotors. In order to do away with the through-shaft construction, the rotor was made of two castings or discs, each of which was cast solid with the shaft, as shown in Fig. 27. The two discs, after machining, were bolted together by a number of very heavy bolts located near the pole tips and, in some cases, shrink links were placed in the pole face, connecting the two halves together. The parallel grooves were then machined in the steel core, just as in the through-shaft type. In this four-pole construction, the problem of armature ventilation was comparatively simple. Air-gap ventilation (that is, all air through the armature core supplied from air-gap) was easily accomplished, due to the open spaces between the poles, which could admit an ample air supply. However, the same construction tended toward high windage losses due to air "churning."

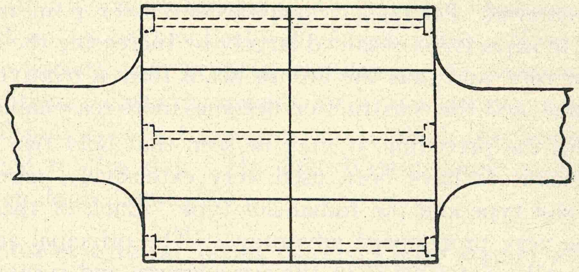


FIG. 27—FIELD CONSTRUCTION WITH TWO HALVES HELD TOGETHER BY HEAVY BOLTS

This problem of ventilation has had much to do with the evolution of turbo-generator design.* In the two-pole, parallel slot machine for 3 600 r. p. m., in which the diameter of the rotor is relatively small, the amount of air which can be forced into the air-gap from each end is rather limited. Assuming, for example, a rotor diameter of 24 inches, which is almost as large as we can go for a 3 600 r. p. m. machine, then, with an air-gap (iron to iron) of $\frac{3}{4}$-inch, which is also a fairly large gap, the total cross-section of the air inlet at the air-gap at both ends of the rotor will be 112 sq. in. With the very high air velocity of 10 000 ft. per minute, this means a total air supply of less than 8 000 cu. ft. per minute. This may be sufficient for a moderate capacity turbo-generator, but for machines of high capacities, such as 3 000 to 5000 k.v.a., this is not nearly enough cooling air. Obviously, either much larger inlets through the air-gap are required, or some additional method of cooling is necessary. Larger air-gaps usually mean either more expensive machines, or reduced output with a given machine, due to lower flux densities. Therefore, the tendency, in machines of the very high capacities, and very high speeds, has been toward a combination of air-gap with other methods of ventilation. In the 25 cycle, two-pole machine with a maximum speed of 1 500 r.p.m., rotors of larger diameter are possible and, as a rule, much larger air-gaps are practicable than in 60 cycle machines. In consequence, air-gap ventilation comes nearer being practicable but in

---

*A more complete exposition of the subject of "Turbo-Alternator Ventilation," etc., is contained in the paper on page 312.

the larger capacities, even this is insufficient and auxiliary methods have been necessary in some cases.

This need for auxiliary methods of ventilation led to the axial method of ventilating armature cores in distinction from the radial method, in which the air was carried out through numerous radial air ducts or passages. In the axial method, a large number of ventilating holes are arranged in the armature core parallel to the axis of the machine. These form ventilating paths in parallel with the air-gap path. With the small diameter long cores necessary for 3 600 r. p. m., high capacity machines, the development of this method of ventilation was contemporaneous with the development of the higher capacities. The same has proved to be the case for the later types of Westinghouse four-pole, 60 cycle, 1 800 r. p. m. machines, which departed very considerably in rotor construction from the four-pole cast steel type already described.

As the capacities of the 3 600 r. p. m., 60 cycle machines were gradually pushed up, a corresponding development occurred in the 1800 r. p. m. machines. At 10 000 to 12 000 k.v.a., the four-pole cast steel construction was apparently approaching its limits. For larger sizes, therefore, a different construction was adopted which allowed more suitable material to be obtained. For the largest diameters and highest speeds, a plate construction was adopted by the Westinghouse Company, in which the end discs and the shaft ends were forged as units, and the intermediate discs were made of rolled plate material, the whole construction being bolted together permanently to form a solid core. This core was then slotted with radial slots, and the usual radial slot type of field winding is used. A similar construction was adopted on the larger 25 cycle machines. For intermediate capacities, both 60 and 25

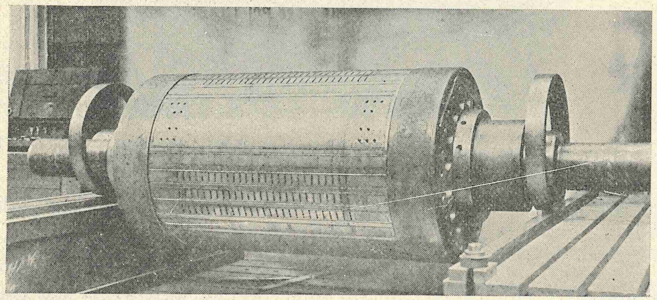


FIG. 28—MODERN ROTATING FIELD ON BALANCING WAYS

cycles, solid discs are used in some cases instead of the plate construction. This brings the larger turbo development up to the present date.

In the comparatively small 60 cycle turbo-generators, where the parallel slot construction with the bronze driving was relatively expensive, as already described, the later development has been towards core and shaft forged in one piece, and with radial slots, and eventually this construction may be carried up to the largest practicable size of 3 600 r. p. m. machines. It is difficult to predict the limit in capacity which may be reached eventually in 3 600 r. p. m. generators, but 6 250 k.v.a. appears to be practicable.

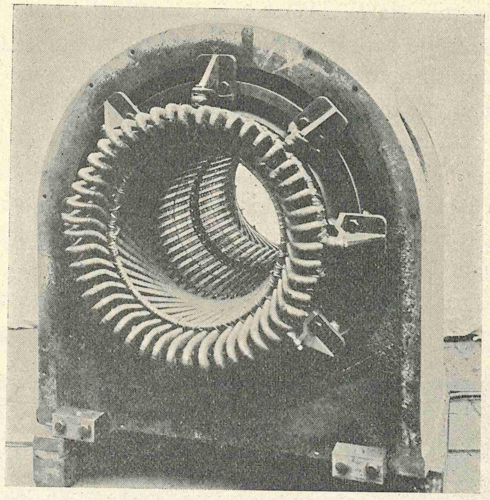


FIG. 29—STATOR OF 625 K.V.A., 2 300 VOLTS, 3 600 R. P. M., TURBO-GENERATOR

With axial ventilation and central duct. Supporting ring both inside and outside the end windings. Typical method of bracing smaller machines.

Some special radial-slot machines had been developed for the New Haven Railroad about 1907. As these machines were designed to deliver 25 cycle single-phase current, and as the pulsating armature reaction of such machines would be relatively high, the rotors were designed with laminated cores, with a view to lessening core losses. The rotors were made of single disc laminations shrunk on the shaft. The discs were provided with radial slots. The construction was very similar to the later radial-slot rotors, except that the rotor end windings were also embedded in slots, and supported by wedges embedded in the periphery of the core, whereas, in the later radial-slot rotors, the end windings are supported by external rings. These early radial-slot rotors showed very considerable overheating in single-phase operation, and it was found necessary to apply a very complete cage damper embedded in the periphery of the rotor. Later experience showed that the solid-core parallel-slot rotor with an equal damper applied to its surface was just as effective, and many of the later single-phase machines were built in this manner. However, some recent 11 250 k.v.a. single-phase generators are being built of the plate construction already described.

Regulation and Short-Circuit Currents of Turbo-Alternators

Like the ordinary synchronous generator, the modern turbo-alternator is designed with a comparatively high inherent regulation. In fact, in order to avoid excessive short-circuit currents, the inherent regulation must be made comparatively poor by making the armature self-induction as high as practicable. Even under the best condition, such machines are liable to give 12 to 15 times rated current during the first current rush. Furthermore, the solid plates or discs, of which most turbo-rotors are now made, tend to prolong the period of maximum short-circuit current. The consequence of these conditions is a tremendous racking force acting on the end windings during a short-circuit current rush, which tends to distort the winding badly unless it is very strongly braced. The Westinghouse Company encountered such a difficulty on some of their earliest turbo-alternators and there has been a practically continuous development along the lines of more substantial bracing which has kept pace with the increased requirements of the higher speeds and the higher capacities. The bracing used on the modern machines is designed to resist distortion of the end windings, under dead short-circuit, without reactances interposed, and each new size as it is developed is given such a short-circuit test. A 20 000 k.v.a. 60 cycle, 1 800 r. p. m. high voltage alternator was recently subjected to such short-circuit tests at full voltage without injury.

The preceding gives a brief history of the development of the turbo-generator, insofar as carried out by the Westinghouse Company. The General Electric Company went through a corresponding course of development, in general, although not in the specific constructions described, and a number of interesting types or constructions have been brought out. The gradual increase in speed has undoubtedly had much to do with the evolution of their various types, just as in the case of the Westinghouse evolution. One of the most radical steps which the General Electric Company has made in the past few years is in the change from the vertical to the horizontal type of machines. Presumably the very high speeds which later came into use have had much to do with this change. In the earlier turbo-generator practice, the speeds of the General Electric Company's machines were relatively lower than the Westinghouse, presumably on account of the type of steam turbine used. Many of the early rotor constructions were of the salient pole type for four poles and higher. Gradually these were superseded by constructions leading up to a radial-slot type in which the slots were formed by teeth inserted in dovetail grooves in the rim of the spider. This type was very similar in appearance to the later types, except that the slots had overhanging tooth tips, thus giving a partially closed slot construction. More recently, with greatly increased speeds, this construction has been superseded by solid forged cores with shaft forged on, and with radial grooves milled in the surface for the field winding. These latter rotors are used largely in the horizontal type high speed machines.

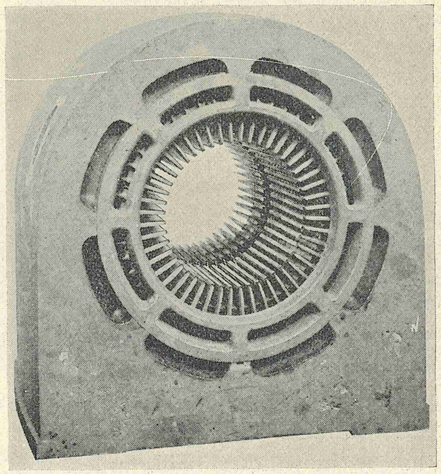


FIG. 30—SAME MACHINE AS SHOWN IN FIG. 29 BEFORE WINDING

In the Allis-Chalmers construction, in the larger machines having four or more poles, the earlier construction of the rotor consisted of forged discs with through shafts. These discs had radial slots for the windings very similar to the present construction of all manufacturers. The smaller machines generally had cores forged in a single piece with the shaft, and with radial windings. As regards methods of ventilation, both the General Electric and Allis-Chalmers Companies went through a course of development leading up to their present practices.

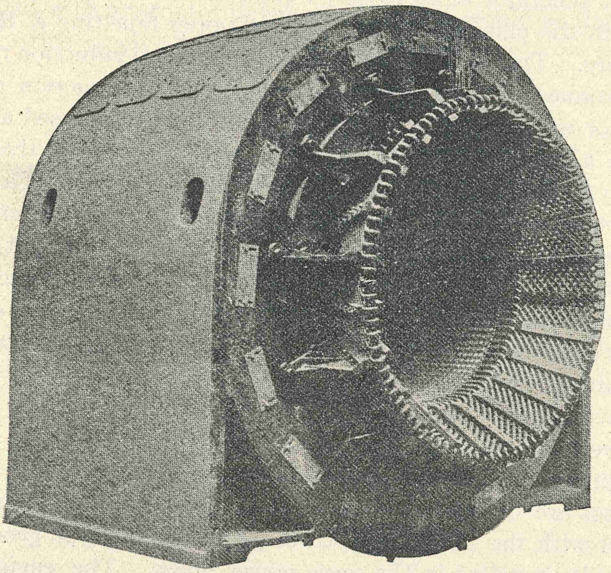


FIG. 31—STATOR OF LARGE MODERN TURBO-ALTERNATOR

As regards parallel operation, turbo-generators have been particularly free from this old time difficulty, due largely to the uniform rotative effort of the steam turbine, and partly to the high flywheel capacity of the turbo-generator and turbine rotors, which tends to limit any speed oscillations, due to the governors, to a relatively low period, such as would not tend to accentuate the hunting action in the generators themselves. Moreover, in those rotors which have been built with solid cores or of thick plates, the solid material tends to act as a damper circuit. As a consequence, hunting in turbo-generators, or difficulties in parallel running, have been extremely rare.

Induction Turbo-Generators

This type of turbo-generator has been proposed commercially a number of times during the past ten years, and a few installations have been built. The first of any importance, consisting of a 1 250 kilowatt generator of 30 cycles, 1 800 r. p. m., two poles, was installed in the plant of the Baltimore Copper Smelting & Rolling Company. This generator was a true polyphase induction motor, direct connected to a steam turbine. The construction of the generator was exactly the same as would have been used at that time in a two-pole, 1 800 r. p. m. induction motor of the same capacity. The entire load of this machine consisted of a 1 200 kilowatt rotary converter connected directly to the terminals of the generator. The genrator and converter were brought up to speed separately and the rotary converter, with its field excited, was connected directly to the generator and furnished the excitation for the generator. There was no other synchronous apparatus in circuit except the converter.

Several years ago, a number of much larger induction generators were built by the General Electric Company for the Interborough Rapid Transit Company of New York City. These machines are of 6 000 k.v.a. nominal capacity and operate in parallel with the 11 000 volt, three-phase, engine-type generators previously installed in the same power house. The engine-type generators furnish the excitation for the induction generators. The entire load of this station is represented by rotary converters. There have been no prominent instances of the use of induction generators for other than steam turbine drive. Apparently this type of generator has no very wide field.

Conclusion

This history is admittedly far from complete, in that it has not mentioned the work of some of the earlier, and also some of the later manufacturing companies. The field is far too large to permit everything to be covered. Moreover, no attempt has been made to describe European constructions and developments in alternating-current generators. It may be stated, however, that in some very important features, European engineers antedated the Americans, while in other equally important constructions American designers were first in the field. As a rule, the representatives of the electrical manufacturing companies have been so

wide awake and ready to adopt new principles when they contained any promise, that it is sometimes very difficult to give any company or individual proper and deserved credit for being first in any given development. Furthermore, no attempt has been made to give credit to the various engineers who have been closely identified with alternator development, for it would be impossible to do justice, or give deserved credit to all of them.

DATA AND TESTS ON 10 000 CYCLE PER SECOND ALTERNATOR

FOREWORD—In 1902, the author undertook the construction of a 10 000 cycle per second alternator. This problem was a very new and radical one at that time and it was considered worth while to put the record of results in permanent form. Therefore, this paper was prepared on the subject and presented before the American Institute of Electrical Engineers in May, 1904. This is interesting merely as a record of a relatively early construction.—(Ed.)

In the early part of 1902, M. Leblanc, the eminent French engineer, was in this country, and spent considerable time at the Westinghouse Electric & Manufacturing Company's works at East Pittsburg. M. Leblanc was very much interested in certain special telephone work, and in connection with such work he desired for experimentation a current of very high frequency. He took up with the writer the question of building a successful alternator for generating current at frequencies between 5000 and 10 000 cycles per second. He was informed that the machine would necessarily be of very special construction, but that it was not an impossible machine. Later he took up the matter with Mr. Westinghouse, who, upon receiving satisfactory assurance that such a machine was possible, advised that the generator be built. A preliminary description of the general design was given M. Leblanc before he returned to Paris. He was somewhat surprised at certain of the features proposed, especially at the fact that an iron-cored armature was considered feasible for a frequency of 10 000 cycles per second.

The machine was designed and built on practically the lines of the preliminary description furnished M. Leblanc. The frequency being so abnormal, the writer believes that many features in the machine, with the results obtained, will be of scientific interest, and therefore the data of the machine, and the tests obtained are presented herewith.

The starting point in this machine was the sheet-steel to be used in the armature. No direct data were at hand showing losses in sheet-steel at such high frequencies, nor was there at hand any suitable apparatus for determining such losses. As preliminary data, tests at frequencies up to about 140 cycles per second were used, and results plotted in the form of curves; these results were plotted for different thicknesses of sheet-steel. Also, tests were obtained showing the relative losses due to eddy currents and hysteresis, and these were plotted, taking into account the thickness of the sheets. These data were not consistent throughout; but the general shape of the curves was indicated, and in this way the probable loss at the frequency of 10 000 cycles per second was estimated for the thinnest sheet-steel which could be obtained. The steel finally obtained for this machine was in the form of a ribbon about 2 in. wide, and about 0.003 in. thick, which was very much thinner than any steel used in commercial dynamos or transformers, which varies from 0.125 to 0.0280 inch. Therefore the machine had to be designed with the intention of using this narrow ribbon of steel for the armature segments.

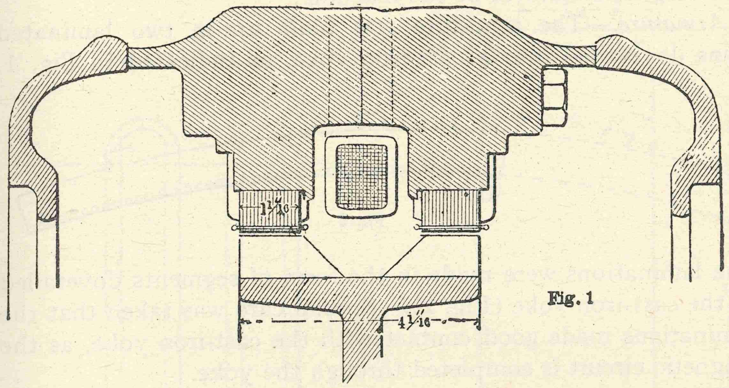


Fig. 1

A second consideration of great importance in the construction of such a machine is the number of poles permissible for good mechanical construction. For instance, at 3000 revolutions—which was adopted as normal speed—the number of poles required is 400 for 10 000 cycles per second. The frequency, expressed in terms of alternations per minute, multiplied by the pole-pitch in inches, gives the peripheral speed in inches. At 1 200 000 alternations per minute (or 10 000 cycles per second) and a pole pitch of 0.25 in., for example, the peripheral speed of the field will be 25 000 feet per minute. It was therefore evident that either a pole construction should be adopted which would stand this high peripheral speed, or the pole-pitch should be less than 0.25 in. It was finally decided that an inductor type of alternator would be the most convenient construction for this high frequency; with the inductor type alternate poles could be omitted, thus allowing 200 pole projections, instead of 400. The field winding could also be made stationary instead of rotating, which is important for such a high speed. This construction required a somewhat larger machine for a given output than if the usual rotating type of machine were adopted; but in a machine of this type where everything was special the weight of material was of comparatively little importance, and no attempts were made to cut the weight or cost of the machine down to the lowest possible limits.

The following covers a general description of the electrical and magnetic features of the machine:

Armature.—The armature was built up in two laminated rings dovetailed into a cast-iron yoke, as indicated in Fig. 1.

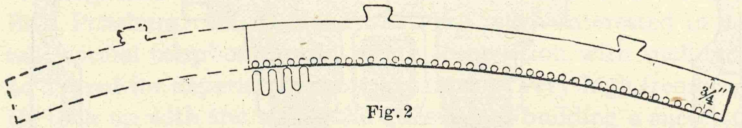


Fig. 2

The laminations were made in the form of segments dovetailed to the cast-iron yoke (Fig. 2). Special care was taken that the laminations made good contact with the cast-iron yoke, as the magnetic circuit is completed through the yoke.

The armature sheet-steel consisted of plates of 0.003 in. thickness. The sheet-steel was not annealed after being received from the manufacturer; it was so thin that to attempt annealing was considered inadvisable. To avoid eddy currents between plates each segment was coated with a thin paint of good insulating quality. This painting was a feature requiring considerable care and investigation, as it was necessary to obtain a paint or varnish which was very thin, and which would adhere properly to the unannealed laminations. These laminations had a bright polished appearance quite different from that of ordinary steel. They were so thin that the ordinary paint or varnish used on sheet-steel made a relatively thick coating, possibly almost as thick as the plates themselves. A very thin varnish was finally obtained which gave a much thinner coating than the plate itself, so that a relatively small part of the armature space was taken up by the insulation between plates.

Each armature ring or crown has 400 slots. Each slot is circular and 0.0625 inch diameter (Fig. 3). There is 0.03125 inch opening at the top of the slot into the air-gap, and the thickness of the overhanging tip at the thinnest point is 0.03125 inch.

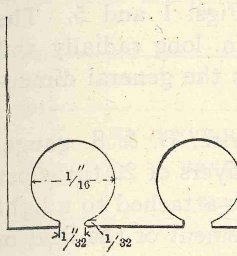


Fig. 3

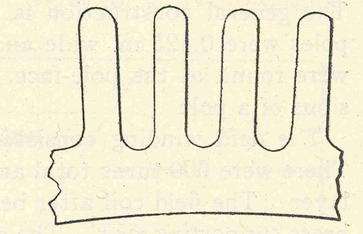


Fig. 5

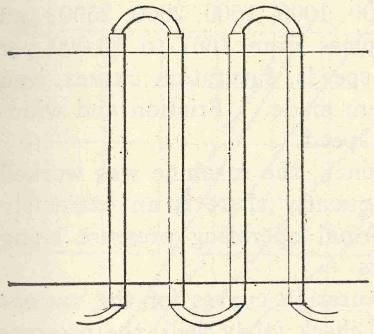


Fig. 4

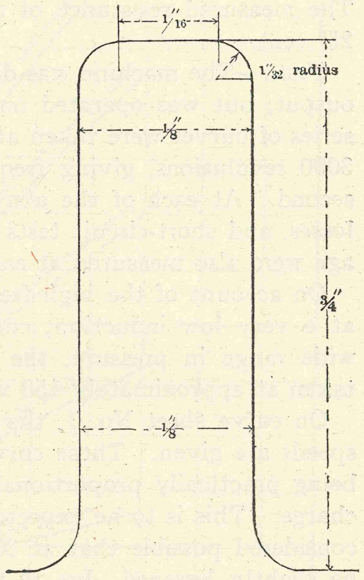


Fig. 6

The armature winding consists of No 22 wire, B & S gauge, and there is one wire per slot The entire winding is connected in series (Fig. 4). The measured resistance of the winding is 1.84 ohms at 25° cent.

After the sheet-steel was built up in the frame, it was ground out carefully. The laminations were then removed, all burred edges taken off and the laminations again built up in the frame. The object of this was to remove all chances of eddy currents between the plates due to any filing or grinding. The finished bore of the armature is 25.0625 inch.

Field or Inductor.—This was made of a forged-steel disc 25 in. diameter turned into the proper shape, and the poles were formed on the outside by slotting the periphery of the ring. The general construction is indicated in Figs. 1 and 5. The poles were 0.125 in. wide and about 0.75 in. long radially and were round at the pole-face. Fig. 6 shows the general dimensions of a pole.

The field winding consisted of No. 21 wire, B. & S. gauge. There were 600 turns total arranged in 30 layers of 20 turns per layer. The field coil after being wound was attached to a light brass supporting ring. The general arrangement of the field or inductor, armature yoke, and bearings, is as indicated in Fig. 1. The measured resistance of the field winding is 53.8 ohms at 25° cent.

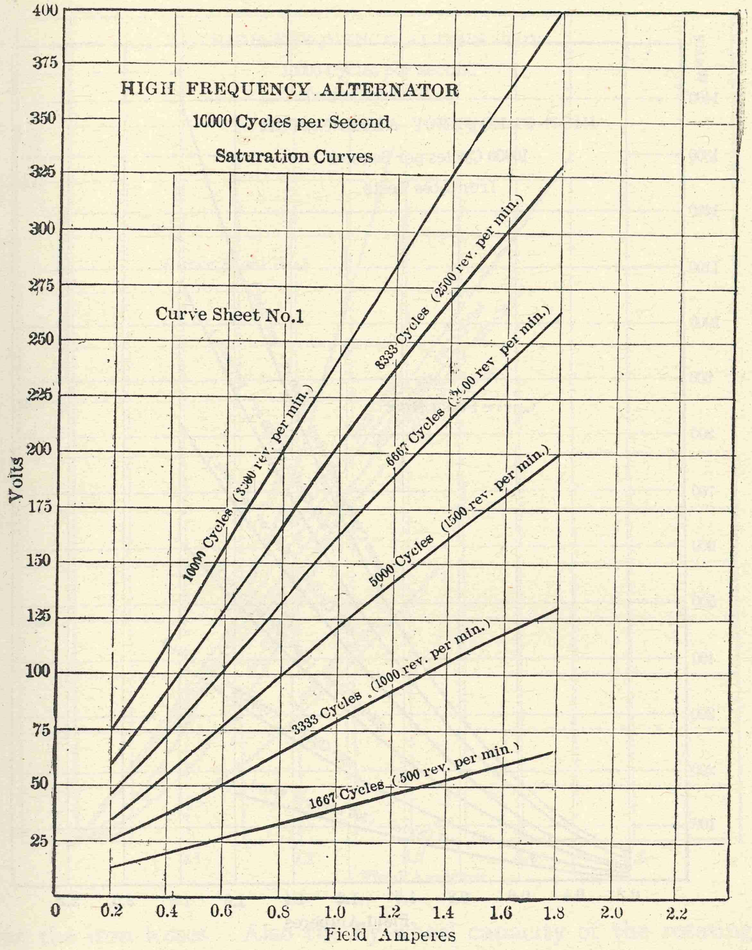
Tests.—The machine was designed primarily for only a small output, but was operated on temporary test up to 2 kw. A series of curves were taken at 500, 1000, 1500, 2000, 2500, and 3000 revolutions, giving frequencies from 1667 to 10 000 per second. At each of the above speeds, saturation curves, iron losses, and short-circuit tests were made. Friction and windage were also measured at each speed.

On account of the high frequency, the machine was worked at a very low induction; consequently there is an extremely wide range in pressure, the normal operating pressure being taken at approximately 150 volts.

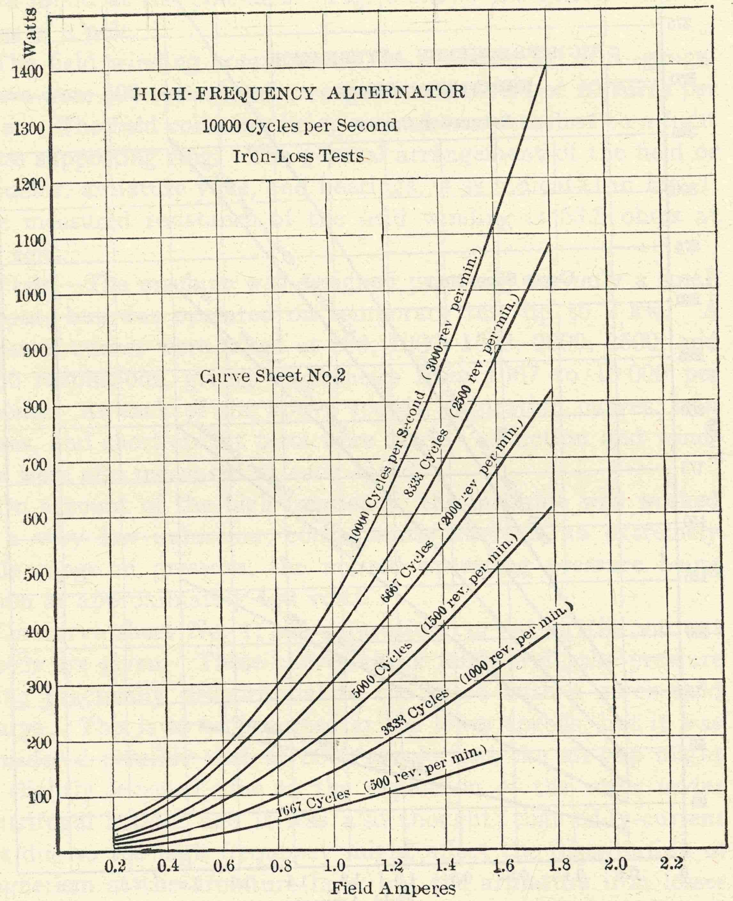
On curve sheet No. 1, the saturation curves for the various speeds are given. These curves check fairly well, the pressure being practically proportional to the speed with a given field charge. This is to be expected at the lower speeds, but it was considered possible that at 3000 revolutions the air-gap might be slightly lessened, due to the expansion of the rotor under centrifugal action; and it was also thought that eddy-current loss due to the high frequency might affect the distribution of magnetism at the armature face; but the armature iron losses were comparatively small, and there appeared to be no such effect. Also there appears to be no effect due to expansion at high speed. The air-gap specified for this machine is 0.03125 in. on each side or 0.0625 in. total gap A very small variation in the diameter of the inductor or the bore of the armature would make a relatively large per cent in the effective air-gap

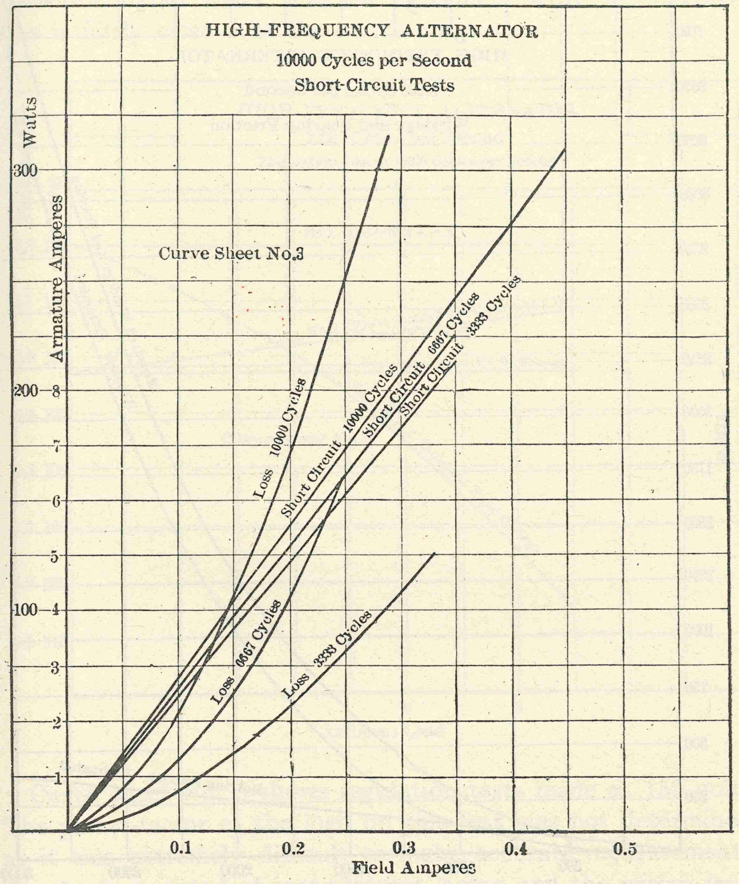
Therefore no reliable calculations can be made on the saturation curves of this machine based upon the specified air-gap.

Curve sheet No. 2 shows the iron losses at various speeds from 500 to 3000 rev per min.—1667 to 10 000 cycles per second. These losses are plotted in terms of watts for a given exciting current. These curves show a rather unexpected condition as regards the losses. According to the original data showing the relative losses due to eddy currents and hysteresis, the eddy-current loss even with these thin plates should have been much higher than the hysteresis loss, but these iron-loss curves show

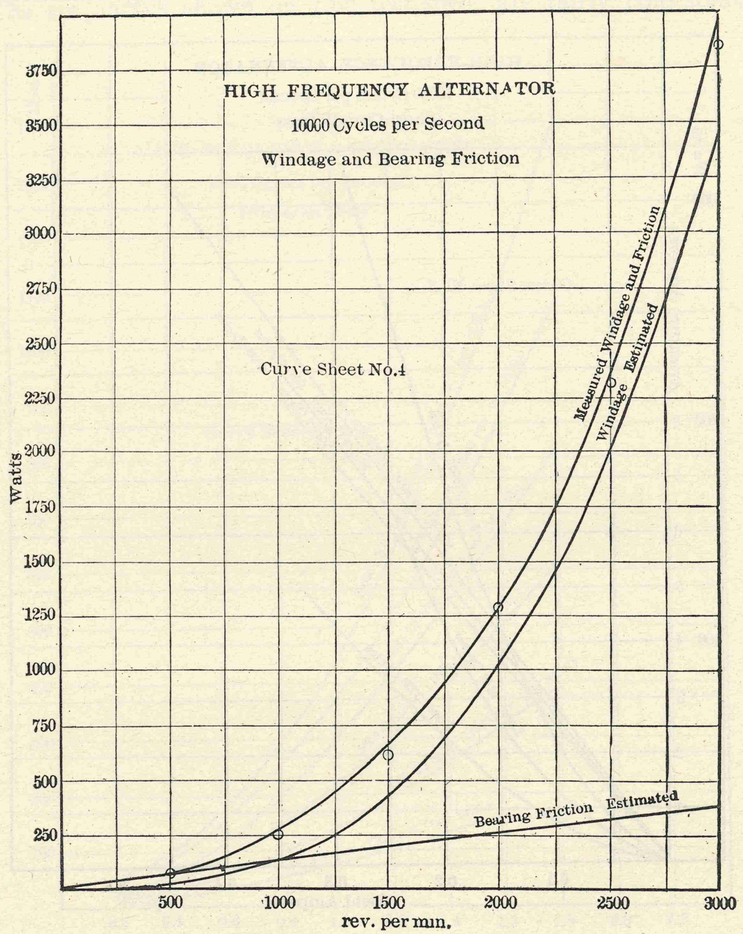


losses with a given field charge almost proportional to the frequency, which is the ratio that the hysteresis loss alone should show. As the eddy-current loss varies as the square of the frequency, the writer expected this to be a large element in the total iron loss, especially at the higher inductions. The six curves shown on this test-sheet are fairly consistent with each other, but it should be remembered that in making measurements of such abnormal apparatus little discrepancies in the curves could easily creep in. For instance, in the saturation curve a series of experiments were first made to find whether usual types of voltmeters were satisfactory, and a number of different methods for checking these readings were used. In determining the iron losses in curve sheet No. 2, the machine was driven by a small motor and the losses measured with different field charges. Under most conditions of test the iron loss was a small element of the total loss, and therefore slight variations in the friction loss would apparently show large variations in the iron losses. Also the fly-wheel capacity of the rotating part of the alternator was comparatively high. Therefore, if there are any variations in the circuits supplying the driving motor, there would tend to be considerable fluctuations in the power supplied. Considering all the conditions of test, the curves appear to be remarkably consistent.



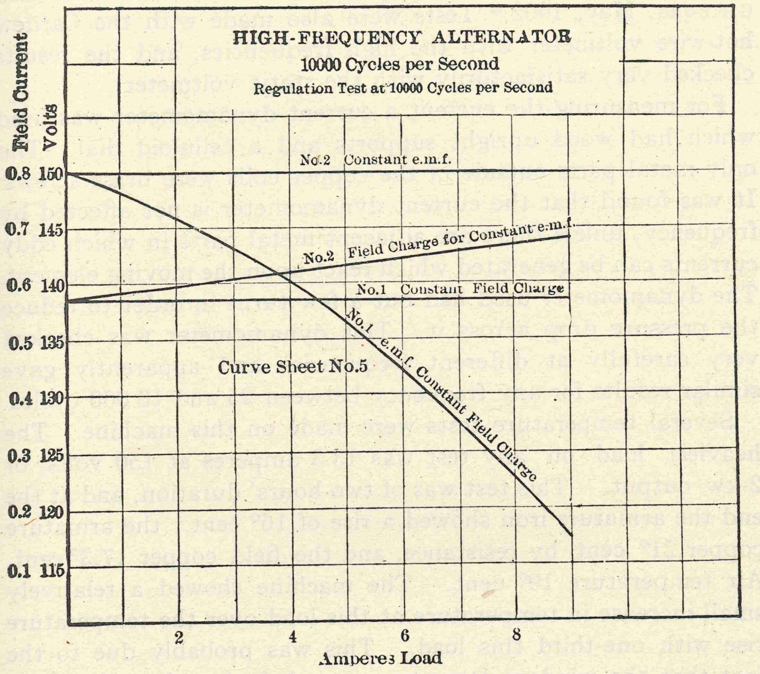


Curve sheet No. 3 shows the short-circuit curves at speeds of 1000, 2000, and 3000 rev. per min., or frequencies of 3333, 6667, and 10 000 cycles per second, respectively. It should be noted that at a given frequency the short-circuit current is proportional to the field current over the entire range measured but that the short-circuit current is not the same for the same field current at the various frequencies. According to these curves the current on short circuit increases somewhat with the given field charge as the frequency is increased.



Curve sheet No. 4 shows the measured windage and friction losses plotted at speeds from 500 to 3000 rev. per min. This

curve indicates clearly that the windage is the principal friction loss at the higher speeds. The writer has added two curves, one showing the estimated bearing friction loss, and the other the estimated windage, based upon the assumption that the bearing friction varies directly as the revolutions and the windage loss with the third power of the revolutions. The small circles lying close to the measured loss curve show the sum of these estimated losses, and the agreement with the measured loss is fairly close over the entire range.



Curve sheet No. 5 shows regulation tests made at 150 volts. The power-factor of the load on this test was not determined, as it was extremely difficult to make accurate measurements. The load consisted of incandescent lamps and the wiring from the machine to the lamps was non-inductive for the usual frequencies; but at the abnormal frequency of 10 000 cycles per second it is more difficult to obtain a true non-inductive load with ordinary apparatus. The tested regulation indicates that the load was practically non-inductive.

In first undertaking tests on this machine there was considerable difficulty in measuring the pressures. It was found that at a frequency of 10 000 cycles per second the Weston voltmeter did not work satisfactorily. Practically the same deflection was obtained on the high and low scales of a 60-120 volt Weston alternating-current direct-current voltmeter with the same pressure.

Very good results were obtained by the use of a form of static voltmeter devised by Mr. Miles Walker. This voltmeter is of the same form as the static wattmeter described by Mr. Walker before the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, May, 1902.* Tests were also made with the Cardew hot-wire voltmeter with the high frequencies, and the results checked very satisfactorily with the static voltmeter.

For measuring the current a current dynamometer was used which had wood upright supports and a celluloid dial. The only metal parts outside of the copper coils were brass screws It was found that the current dynamometer is not affected by frequency, unless there are adjacent metal parts in which eddy currents can be generated which react upon the moving element. The dynamometer used had but a few turns in order to reduce the pressure drop across it. This dynamometer was checked very carefully at different frequencies and apparently gave similar results for any frequency between 25 and 10 000 cycles

Several temperature tests were made on this machine. The heaviest load on any test was 13.3 amperes at 150 volts, or 2-kw. output. This test was of two hours' duration, and at the end the armature iron showed a rise of 16° cent.; the armature copper 21° cent. by resistance, and the field copper 17.3° cent. Air temperature 19° cent. The machine showed a relatively small increase in temperature at this load over the temperature rise with one-third this load. This was probably due to the fact that the windage loss was so much higher than the other losses of the machine that the temperature was but little affected by the small additional loss with increase in load.

Attempts were made to utilize the current from this machine for various experiments, but difficulty was at once found in transforming it. At this high frequency no suitable iron-cored transformer was available. Transformers with open magnetic circuits were tried and operated better than those with iron cores but were still rather unsatisfactory. It was decided that nothing could be done in this line without building special transformers.

[*TRANSACTIONS of the A. I. E. E., Vol. XIX, p. 1035.]

Among the few experiments made was that of forming an arc with current at this high frequency. This arc appeared to be like an ordinary arc so far as the light was concerned, but had a very high-pitched note corresponding to the high frequency. This note was very distressing to the ears.

This machine is in reality of the nature of a piece of laboratory apparatus; and at present it has no commercial value. It was designed primarily for scientific investigation, and appears to be a very good machine for that purpose.